Contract ERS 77-19467

TECHNOLOGY ASSESSMENT OF ADVANCED COMPOSITE MATERIALS

PHASE I

FINAL REPORT

April 1978

Prepared for

National Science Foundation
Washington, D.C. 20550

This research was conducted with the support of the National Science Foundation. However, any opinions, findings, conclusions or recommendations expressed in this report are those of the author and do not necessarily reflect the views of the NSF.

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ABSTRACT

TECHNOLOGY ASSESSMENT OF ADVANCED COMPOSITE MATERIALS - PHASE I FINAL REPORT

By R. Kaiser, Argos Associates, Inc.

Contract ERS 77- 19467

The principal high performance fibers currently used in advanced composites are graphite, aramid, and boron. In the future, these will be supplemented by other high strength fibers such as alumina, silicon carbide, and boron nitride. Organic matrix composites, which are evolutionary products of fiberglass reinforced plastics, predominate the technology. Carbon/carbon matrix composites, now mainly used in missile components and aircraft brakes, may find medical use as implantable substitutes for bone structures. Metal matrix composites are currently used in aerospace applications of a developmental nature. With further technical development, metal matrix composites, especially short fiber composites, may be used in specialty applications, particularly in energy conversion systems.

In 1977, 360 metric tons of high performance fibers, with a total value of $30 million, were consumed in the U.S. This is approximately 0.1% of the U.S. consumption of fibrous glass, but about 7% of the value of fiberglass sales. Advanced composites technology appears to be on the verge of significant growth. In the past, advanced composites were principally used in specialized applications which placed a high premium on performance. These materials are now being considered, on an experimental basis, for applications that are sensitive to first costs. The most important of these are automobiles, trucks, aircraft, pollution control equipment and agricultural machinery. In the year 1990, it is projected that the consumption of high performance fibers, mainly graphite and aramid, may range from 25,000 to 100,000 metric tons per year, with a projected sales value of between $700 million and $1.3 billion.

The commercialization of advanced composites will result in impacts that will be similar to, and marginal to, those of fiberglass reinforced plastics. High performance fibers will be catalysts for increased consumption of glass fibers in reinforced plastics, but otherwise not affect other basic materials. Areas of application of advanced composites that could result in significant secondary impacts are automotive equipment, general and commercial aviation, agriculture, and the industrialization of space. Advanced composites can be a major tool for petroleum energy conservation, especially in transportation. It is estimated that extensive use of advanced composites could result in an additional reduction in petroleum energy consumption of 1.5 Quads/yr over a projected fuel efficient 1985 base line. By 1990, the projected use of advanced composites may result in an actual reduction of about 10% of this value. A current concern specific to graphite composites is the potential interference with electrical systems by conductive graphite filaments released into the atmosphere as a result of an accident or a fire.

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Last, but not least, the continuing help and support of Dr. Val Krukonis, Arthur D. Little, Inc., Cambridge, MA. during the course of this program, were particularly appreciated. His expert knowledge of the technology and his entree to the advanced composites community were of great help to the program.

Robert Kaiser
Principal Investigator

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1.0 INTRODUCTION

1.1 SCOPE OF STUDY

Technology assessments are policy studies which systematically define, explore, and evaluate the full range of economic, social, environmental, institutional, and other consequences of the introduction of a new technology in our society or the expansion of an extant technology, more extensively, intensively or in new ways.

The present report summarizes the results of a planning phase of a technology assessment of advanced composite materials. As defined in the original RFP issued by the National Science Foundation, advanced composites result from combinations of graphite fibers, boron fibers and/or new polymer fibers with the potential for being used as industrial materials in a number of applications.

In this Phase I report, the state of the art and the potential development and application of those radically new materials have been assessed in order to obtain a better understanding of the overall consequences of their widespread use. The potential effects of these materials on the economy, national energy requirements, the labor force, the environment, health, industrial organizations, and product marketing, use, replacement and disposal have been considered.

The purpose of this planning phase was to develop a feasible and definitive study approach, including supporting data and illustrative analytical procedures, that would form the basis for the completion of a comprehensive technology assessment under a subsequent Phase II program.

1.2 OVERALL APPROACH TO PHASE I

The overall approach to the problem was to develop a list of questions, which when answered, would provide a complete understanding

of the present and future positions of advanced composites in the National Economy. In a technology assessment study of this nature, the difficult task is to define the scope of the effort and to insure that all the right questions will have been asked. Developing the answers to the questions, although a time consuming task, lends itself to straightforward analysis and is usually relatively simple.

Table 1-1 presents the major pertinent issues that were originally perceived by ARGOS Associates to be relevant to a technology assessment of advanced composite materials. Based on past experience, at the time the initial proposal was prepared in April 1977, it was felt that any Phase II program would have to address all the issues outlined in Table 1-1.

In Phase I, the perspective and completeness of the scope of issues outlined in Table 1-1 were assessed by collecting substantiating data from cognizant sources. These sources included, beyond the standard literature, attendance at six technical meetings, and extensive contacts and interviews with the major factors in the emerging advanced composite materials industry. Contacts were developed and maintained with representatives of involved private sector manufacturing and end-user organizations, academic researchers, consultants, as well as with those government agencies that are actively studying and supporting the expanded use of advanced composite materials. A list of these contacts is presented in Appendix A.

The results of this aspect of the study are presented in Section 2.0, which presents an overview of the current state of advanced composites technology and identifies major trends. This survey is arranged in the following order:

a) Overview
b) Fiber Technology
c) Organic Matrix Composites (resins, mill products, fabrication)

TABLE 1-1

INITIAL PERCEPTION

SCOPE OF ISSUES RELEVANT TO A TECHNOLOGY ASSESSMENT OF ADVANCED COMPOSITES

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f) Applications of Advanced Composites

The potential impacts of advanced composites technology are identified and scoped in Section 3.0. Section 4.0 presents a list of current federal appropriations actions, laws and regulations which could impact advanced composites technology as a way of scoping the potential interaction of this technology and government policy.

1.3 MAJOR FINDINGS

The principal high performance fibers currently used in advanced composites are graphite, aramid and boron. In the future, these will be supplemented by other high strength fibers such as alumina, silicon carbide, and boron nitride, among others. Organic matrix composites predominate the technology. Carbon/ carbon matrix composites are developed sufficiently for use in the specialty applications that have been identified, mainly missile components and aircraft brakes. Carbon matrix composites may find wide medical use as implantable substitutes for bone structures. Metal matrix composites are currently used in aerospace applications of a developmental nature; and the technology requires significantly further development if metal matrix composites are to become competitive structural materials. However, metal matrix composites, especially short fiber composites, may be used in specialty applications, particularly in energy conversion systems, where certain metals or alloys are now used in spite of their inherently poor structural properties (i.e. lead).

Advanced organic matrix composites are evolutionary products of fiberglass reinforced plastics (FRP).

The current total U.S. consumption* of all high performance fibers is estimated to be about 800,000 lbs/yr, or approximately 0.1% of the consumption of glass fiber. Depending on the material, high

* excluding tire reinforcements

performance fibers range in price from about $8/lb. to over $200/lb. Even though the unit costs of the fibers are significantly lower than they were ten years ago, they are still high when compared to the E glass fiber at 49 cents/pound. The total value of high performance fibers consumed in U.S. in 1977 is estimated to be $30 million or about 7% of the value of glass fiber sales.

The above figures indicate that advanced composites technology is still an immature technology. This view is further reinforced by comparing the value of the high performance fibers sold to the research and development funds that are currently being allocated to advanced composites, by various government agencies and private industry in the U.S. which are significantly larger than the value of the high performance fibers sold for all applications. For example, NASA alone allocated $30 million to the support of advanced composites technology in FY 1977. The total current R&D allocations from all sources are estimated to be of the order of $100 million/year to $200 million/year.

Advanced composites technology appears to be on the verge of significant growth. In the past, advanced composites were principally considered for specialized applications where performance requirements were at premium and first cost considerations were secondary. The technology has advanced to the stage where these materials are now being considered, on an experimental basis, for applications for which first cost considerations have to be taken into account. If performance and cost criteria can be simultaneously achieved, advanced composites would find significant commercial use. Some of these applications are automobiles, trucks and aircraft. Other major potential applications that were identified during the course of the program were agricultural machinery and pollution control equipment.

In the year 1990, it is projected that consumption of high performance fibers, mainly graphite and aramid, may range from 25,000 to 100,000 metric tons per year. At this consumption level, the projected

average price, in constant dollars, of these high performance fibers will be between \$6/lb (\$13/kg) and \$12/lb (\$26/kg). The projected value of high performance fiber sales will be between \$700 million and \$1.3 billion, or about \$1 billion. In greatest part, these fibers will be mixed with fiber glass and incorporated in resin matrix composites.

The commercialization of high performance fibers, and their use in advanced composites, will result in relatively little dislocation of other basic materials or industries. High performance fibers will have the greatest impact on fiberglass. In this case, they will act as catalysts for increased consumption of glass fibers in reinforced plastics. Advanced composite structures can be a major tool for petroleum energy conservation, especially in the transportation sector. It is estimated that extensive use of advanced composites could result in a reduction in petroleum energy consumption of 1.5 Quads/yr, or 250 million barrels of oil per year, over a 1985 projected baseline which already considers a fuel efficient automotive fleet. By 1990, the projected usage of advanced composites will result in a probable reduction in fuel consumption of about 10% of this value, or 25 million barrels/year. Areas of application of advanced composites that could result in significant secondary impacts are automotive equipment, general and commercial aviation, agriculture, and the industrialization of space. In general, the other impacts of advanced composite technology will be similar in nature, and marginal, to those of fiberglass reinforced plastics technology which will expand over four fold by 1990. A particular exception of current concern is that the uncontrolled release of conductive graphite fibers could potentially interfere with electrical systems.

2.0 STATE OF THE ART SURVEY

2.1 INTRODUCTION

Composite materials are combinations of two or more distinct solid materials that are bonded to each other in order to combine the properties of the component parts, to obtain composite properties which may be new or unique. They have long been used to fabricate useful artifacts and products. Wood and bone are natural composite materials that have been used since time immemorial. The credit for developing the first engineering composite most probably belongs to the early Egyptians who found that by gluing a number of thin strips of wood together, a product of superior properties was obtained. The armorers of Japan also understood the advantages to be derived from composite materials. The outstanding performance of the Samurai blade was a result of the craftmanship of these sword makers and their ability to combine steel and iron to form a blade that has an extremely hard and keen edge while retaining a flexible body. At present, a myriad of combinations of metals, ceramics, and nonmetallic materials, all of which can properly be called composites, are in engineering use.

Reinforced plastics are noteworthy examples of a class of composite materials that have reached commercial fruition. The first U.S. patent (U.S.P. 1,393,541) for a structural reinforced plastic was filed May 26, 1916 by Robert Kemp and assigned to Westinghouse Electric and Manufacturing Company. Little was done with this technology until World War II when fiberglass reinforced plastic proved to be an advantageous material for fabricating radomes and radar housing. After World War II, consumption dropped until commercial applications were identified and technology developed to meet these requirements. After a short lull, the demand increased once more, and the growth of the FRP (fiber-reinforced plastics) industry has been spectacular as is shown in Figure 1-1. The post war lull is indicated in this Figure. In 1977, the estimated demand for reinforced plastics was nearly 1.8 billion lbs. as shown in

Figure 2.1, with an overall annual growth rate of 12 percent.[1] The combination of thermosetting resins with glass fibers accounted for the bulk of reinforced plastics products, and the glass fiber industry has grown in conjunction with the reinforced plastics industry. In 1977, glass fiber industry capacity was 967 million lbs. (439,000 metric tons), with shipments of 834 million lbs. (379,000 metric tons).[2] Based on the current value of glass fibers (E glass) of $0.49/lb, the value of this product was $409 million. By 1981, industry capacity and shipments are expected to increase by 50%, which corresponds to a growth rate of 11% per year. At this growth, the industry will quadruple by 1990.

Approximately two decades ago, in order to meet the increasing requirements of advanced military systems, a number of low density fibers were produced that were significantly stiffer than glass fibers with comparable, or superior, strength properties. In the ensuing years, the category, high performance fibers, has grown to include such diverse materials as boron, carbon, aramid (an organic compound), silicon carbide, and alumina.

Concurrently, as the availability of these fibers increased, and their price fell by two orders of magnitude, it became possible to consider using these materials in a variety of non-aerospace applications, a transition similar to the one experienced by fiberglass.

The principal physical properties of the high performance fibers that are currently commercially available in the U.S. are presented in Table 2-1. The properties of E-glass fiber most commonly used in reinforced plastics and of higher strength S glass fibers developed for the aerospace market are also included in Table 2-1 for purposes of comparison. The principal physical properties of high performance fibers presently under development and that may be commercially available in the future are presented in Table 2-2.

Incorporating one or more of these high performance filaments in a suitable matrix produces a class of composite materials that exhibit physical and structural properties not unattainable with conventional engineering materials. The matrix can be a thermosetting resin, such as an epoxy, polyester, or polyimide; a thermoplastic resin, such as nylon or polysulfone; a metal, such as aluminum or titanium; or a ceramic such as glass.

The mechanical properties of fibrous composites depend principally on the type, volumetric concentration, and relative orientation of fibers in the matrix, as is discussed in Appendix B. In synopsis here, fibrous composites are strongest and stiffest in the direction of the fibers where the mechanical properties of the fibers predominate and are relatively weak in the direction normal to the fiber where the matrix properties predominate. This is a very different situation than exists for homogeneous materials of construction, such as aluminum and steel, which exhibit isotropic mechanical properties. Because of the directional nature of the structural properties of composites the design of components made from composites is more difficult than for components made from homogeneous materials, and a better understanding of the stresses the component will experience in service is required. These non-isotropic characteristics, however, can also be an asset to a designer who can tailor a composite by selectively positioning the reinforcing fibers to meet specific requirements.

The major attribute of advanced structural composites is their combination of high strength and high stiffness with low density. Structures made of composites are usually much lighter than structures of comparable strength and/or stiffness made of standard materials of construction such as aluminum or steel.

Figure 2-2 compares the longitudinal tensile strength and tensile modulus of the composites listed in Table 2-3 with those of aluminum and steel. It is to be noted that the composite materials exhibit

higher strength than steel and aluminum. In addition, the carbon and boron composites are all much stiffer than aluminum, with stiffness comparable to that of steel, and the very high modulus carbon/epoxy has nearly twice the modulus of steel. The modulus of the aramid-epoxy composite is comparable to that of aluminum, whereas the modulus of fiber glass-epoxy is lower than that of aluminum.

The inherent advantage of using advanced composite structures is demonstrated more graphically in Figure 2-3 which compares the specific strength, i.e. strength to density ratio, and specific modulus, stiffness to density ratio, of the advanced composites with those of traditional materials. Consideration of specific properties allows a comparison to be made on a unit weight basis. On a specific basis, all the composites are all much stronger than steel or aluminum; however, only the advanced composites are stiffer on a specific basis than the metals, while the specific stiffness of fiberglass-epoxy composites is slightly lower than that of steel or aluminum. Advanced composites differ from the more traditional fiberglass composites in that they can exhibit both a significantly higher specific modulus as well as a significantly higher specific strength than those of the traditional metals.

Figure 2-2 presents the advanced composites to their best advantage by focusing on the longitudinal properties of uniaxial composites. However, considerable performance improvement is still obtained with quasi-isotropic composites relative to metals, as is discussed in Appendix B.

The excellent fatigue properties of advanced composites are another of their major attributes. Figure 2-4 illustrates the fatigue resistance of uniaxial advanced composites compared to those of other materials. The three advanced composite materials presented in Figure 2-2 have a residual strength of about 70% of the static value after 10 million cycles, which is significantly higher than the strength retention of either aluminum, steel or fiber glass-epoxy composites. The

FIGURE 2-1

GROWTH OF THE REINFORCED PLASTICS INDUSTRY

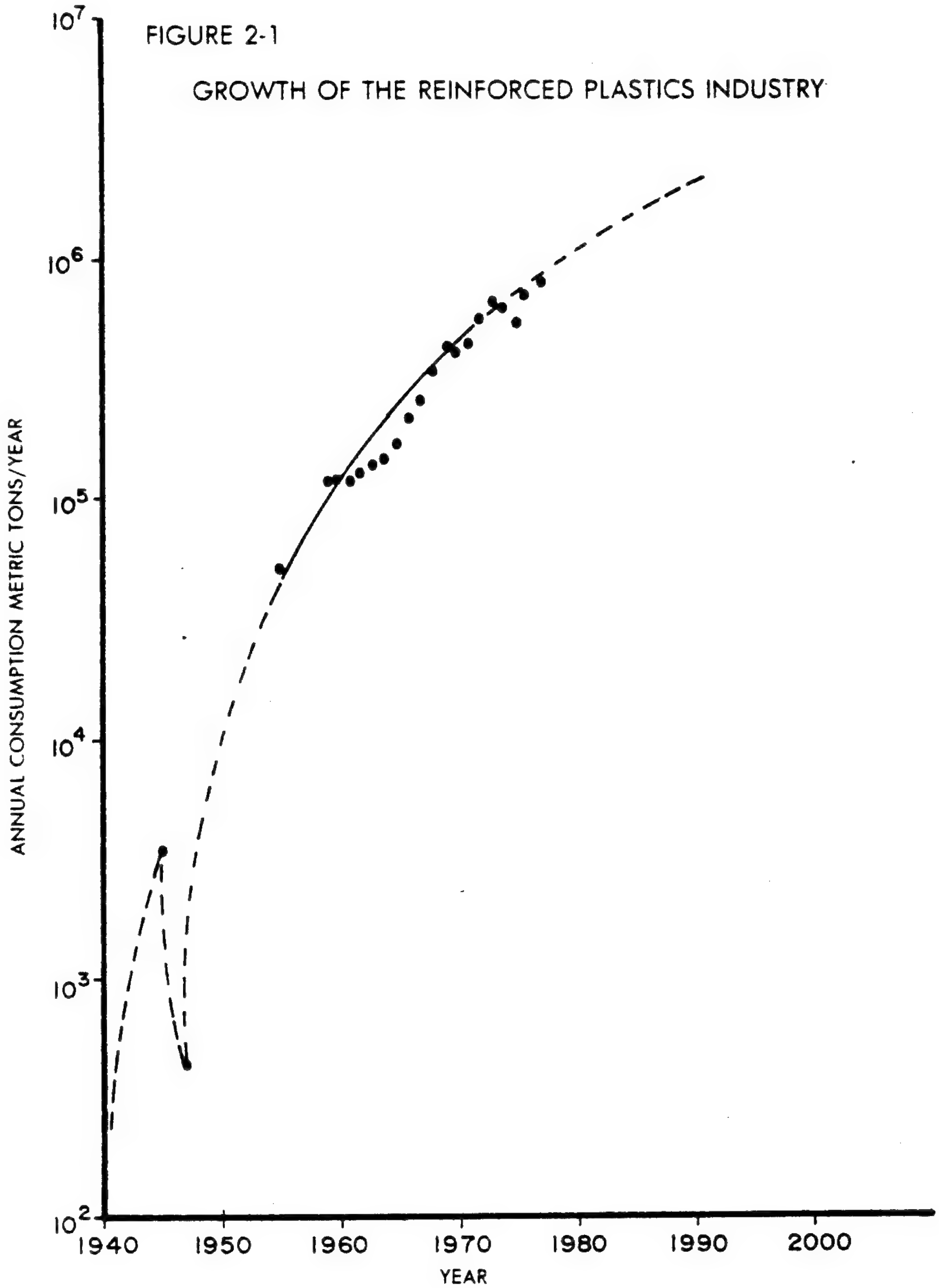


TABLE 2-1 PHYSICAL PROPERTIES OF COMMERCIALLY AVAILABLE HIGH STRENGTH FILAMENTS

					Graphite Filaments		
Material	E-Glass Fiber	S-Glass Fiber	Aramid Fiber	Boron/Tungsten Fiber	High Strength Fiber	High Modulus Fiber	Very High Modulus Fiber
Product	(Roving)	(Roving)	Kevlar 49	5.6 mil Diam.	Thornel 300 (WYP 15-1/0)	Magnamite HMS	Celion GY-70
Supplier			Dupont	Avco/CTI	Union Carbide	Hercules	Celanese
Density lbs/in^3	0.092	0.090	0.052	0.090	0.062	0.067	0.071
g/cm^3	2.54	2.48	1.44	2.48	1.72	1.86	1.96
Tensile Strength 10^3 psi	372	550	400	500	360	340	270
MPa	2500	3700	2800	3400	2600	2300	1900
Tensile Modulus 10^6 psi	10.5	12.4	18.0	58.0	32.5	50	75
GPa	73	86	124	406	225	350	520
Ultimate Elongation, %	4.8	5.4	2.5	0.8	1.1	0.58	0.38
Specific Strength, in	$4.0x10^6$	$6.0x10^6$	$7.9x10^6$	$5.6x10^6$	$6.1x10^6$	$5.0x10^6$	$3.8x10^6$
cm	$9.8x10^6$	$1.5x10^7$	$1.9x10^7$	$1.4x10^7$	$1.5x10^7$	$1.2x10^9$	$9.7x10^6$
Specific Modulus, in	$1.1x10^8$	$1.4x10^8$	$3.5x10^8$	$6.4x10^8$	$5.2x10^8$	$7.5x10^8$	$1.1x10^9$
cm	$2.9x10^8$	$3.5x10^8$	$8.6x10^8$	$1.6x10^9$	$1.3x10^8$	$1.9x10^9$	$2.7x10^9$
Filament Diameter, mils	0.20-0.55	0.35-0.40	0.47	5.6	0.3	0.3	0.33
cm	0.0005-0.014	0.0009	0.0012	0.014	0.0007	0.00075	0.00084
Thermal Conductivity BTU-ft/hr $(ft^2)(^oF)$	0.56				12	70	
W/m ^oK	0.97				20.8	121	
Electrical Resistivity Ω mil ft					9000	4500	3900
μΩcm					1500	750	650
Current Price, $/lb	0.49	2.00	8-10 & up to 27 for fine denier fiber	200	32	70	110-250

TABLE 2-2

Physical Properties of Developmental High Strength Fibers

Material	Pitchbase Graphite	Boron/Carbon	Silicon Carbide/Carbon	Alumina	Boron Nitride
Product	Thornel P-VSB-32			FP	
Manufacturer	Union Carbide	AVCO	AVCO	DuPont	Carborundum
Density lbs/in^3	0.073	0.082	0.113	0.143	0.065-0.069
g/cm^3	2.02	2.26	3.11	3.95	1.8-1.9
Tensile Strength 10^3psi	200	475	450	200	120 (ave.)
MPa	1380	3300	3100		830
Tensile Modulus 10^6psi	50	53	62	55	30 (ave.)
Gpa	345	363	425	377	210
Ultimate Elongation %	0.4			0.4	
Specific Strength in.	2.8×10^6	5.8×10^6	4.0×10^6	1.4×10^6	1.8×10^6 (ave.)
cm	6.8×10^6	1.5×10^7	1.0×10^7	3.6×10^6	4.7×10^6
Specific Modulus in.	6.8×10^8	6.4×10^8	5.5×10^8	3.5×10^8	4.6×10^8 (ave.)
cm	1.7×10^9	1.6×10^9	1.4×10^9	8.9×10^8	1.2×10^9
Filament diameter mils	0.44	5.6	5.6	1.0	0.24
cm	0.0011	0.014	0.014	0.002	0.0006
Thermal Conductivity BTU ft/hr(ft^2)(^{o}F)	48			0.074	1.7
W/m^{o}K	83			0.13	3.0
Electrical Resistivity, ohm-cm					10^{14}
Current Price \$/lb	20	250	450	200	

TABLE 2-3

Room Temperature Properties of Commercial Unidirectional Fibrous Epoxy Composites

Fiber Manufacturer			DuPont	AVCO or CTI	UCC	Hercules	Celanese
Fiber Type	E-Glass	S-Glass	Aramid (Kevlar-49)	Boron/W 4mil	Thornel 300 Graphite	HMS Graphite	GY 70 Graphite
Fiber Volume %	60	60	60	50	60	62	60
Prepreg Mfg	3M	Fiberite	DuPont	3M	Fiberite	Hercules	Narmco
Prepreg Type	1009-26	HY-E 9034B	PR 286	SP292	HY-E 1076C	HMS 3501/6	5208
Density lbs/in^3	0.072	0.075	0.050	.068	0.058	0.059	0.062
gr/cm^3	2.00	2.08	1.38	1.88	1.61	1.63	1.72
Longitudinal (0^o) Properties							
Tensile Strength $10^3 psi$	185	235	200	186-232	233	120	98
MPa	1280	1620	1380	1280-1600	1610	830	680
Tensile Modulus $10^6 psi$	5.7	8.5	11	29.6-32.0	21.5	28	51
GPa	39	59	76	204-220	148	193	352
Flexural Strength $10^3 psi$	200	270	90	245	298	140	115
MPa	1380	1860	620	1690	2060	966	794
Flexural Modulus $10^6 psi$	7.0	8.5	10	28	21.5	24.5	40.0
GPa	48	48	69	193	148	169	276
Compressive Strength $10^3 psi$	90		40	443-460		55	
MPa	620		280	3060-3180		380	
Compressive Modulus $10^6 psi$			10.5	35.0-35.5		15.5	
GPa			72	242-545		107	
Transverse (90%) Properties							
Tensile Strength $10^3 psi$			4.3	9.8-17.8		4.5	
MPa			30	68-123			
Tensile Modulus $10^6 psi$			0.8	3.16-3.92		1.1	
GPa			6	21.8-27			
Interlaminar Shear $10^3 psi$		.14	8.7	17	17	8.0	8.5
MPa		97	60	11.7	117	55	59

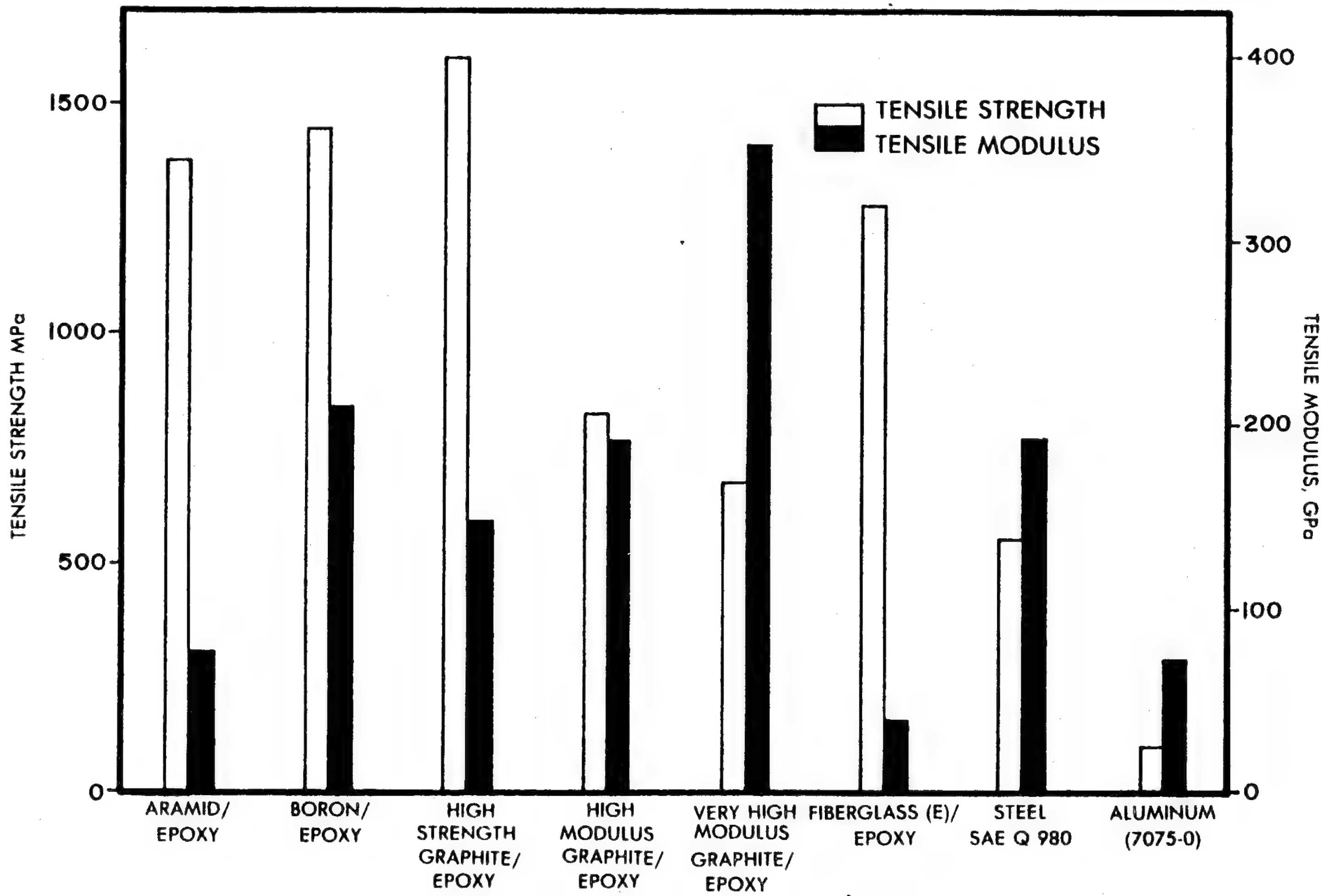


FIGURE 2-2 TENSILE PROPERTIES OF MATERIALS OF INTEREST

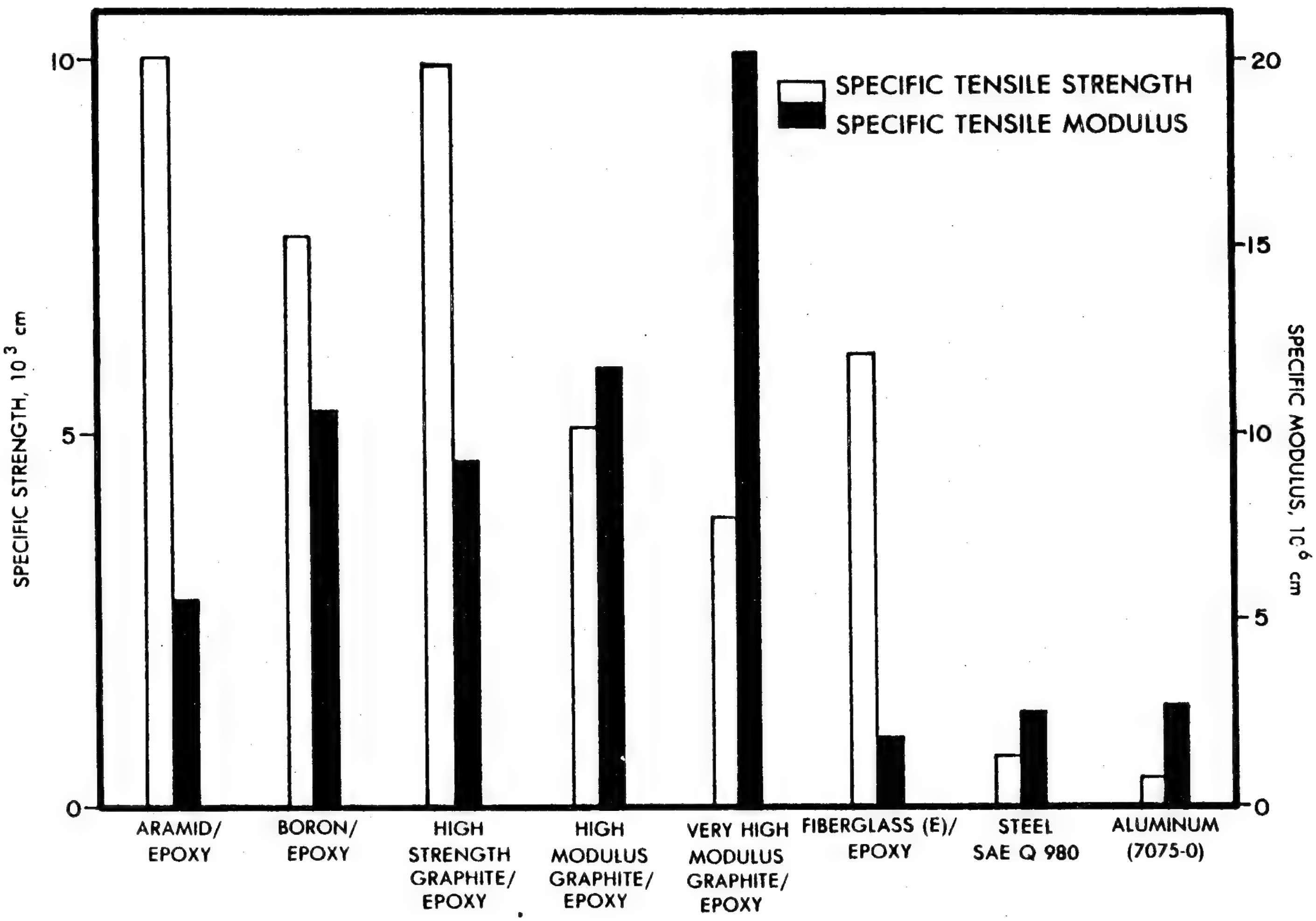


FIGURE 2-3 SPECIFIC TENSILE PROPERTIES OF MATERIALS OF INTEREST

significantly better fatigue characteristics of the advanced composites than those of fiberglass composites are striking. Since many useful structures (such as machinery and transportation equipment) are often designed for fatigue rather than for strength, the excellent fatigue characteristics of advanced composites as compared to other materials further enhances the weight reduction that can be achieved by the use of these composites in highly stressed fatigue critical structural parts.

Still another general attribute of high performance composite is their tendency to dampen vibrations more rapidly than materials that are not as stiff.

It should not be inferred from the above that all advanced composites have similar or equivalent properties. Each of the high performance fibers has unique properties that differentiate it from other fibers as outlined in Table 2-4. In addition to the general high strength, high modulus characteristics observed above, a specific composite will have other properties which will make it a better choice for a specific application than another composite. In fact, the material properties desired for a given component may best be achieved with hybrid composites which are mixtures of different filaments in a common matrix. Hybridization greatly expands the range of properties that can be achieved with composites. The concept of hybridization also blurs the distinction between the advanced composites, as previously defined herein, and the more generally established fiber reinforced materials such as glass fiber reinforced plastics. Depending on the ratio of carbon fiber to glass fiber in the composite, hybrid carbon/glass-epoxy hybrids will exhibit a significant range in properties. Furthermore, if the stiffer carbon fiber is selectively placed in the structure, the overall properties (such as stiffness and fatigue) of the structure may be enhanced disproportionately to the amount of carbon fiber added.

Most of the environmental properties of advanced composites materials are a function of the matrix material rather than the high

FIGURE 2-4 FATIGUE RESISTANCE OF MATERIALS OF INTEREST

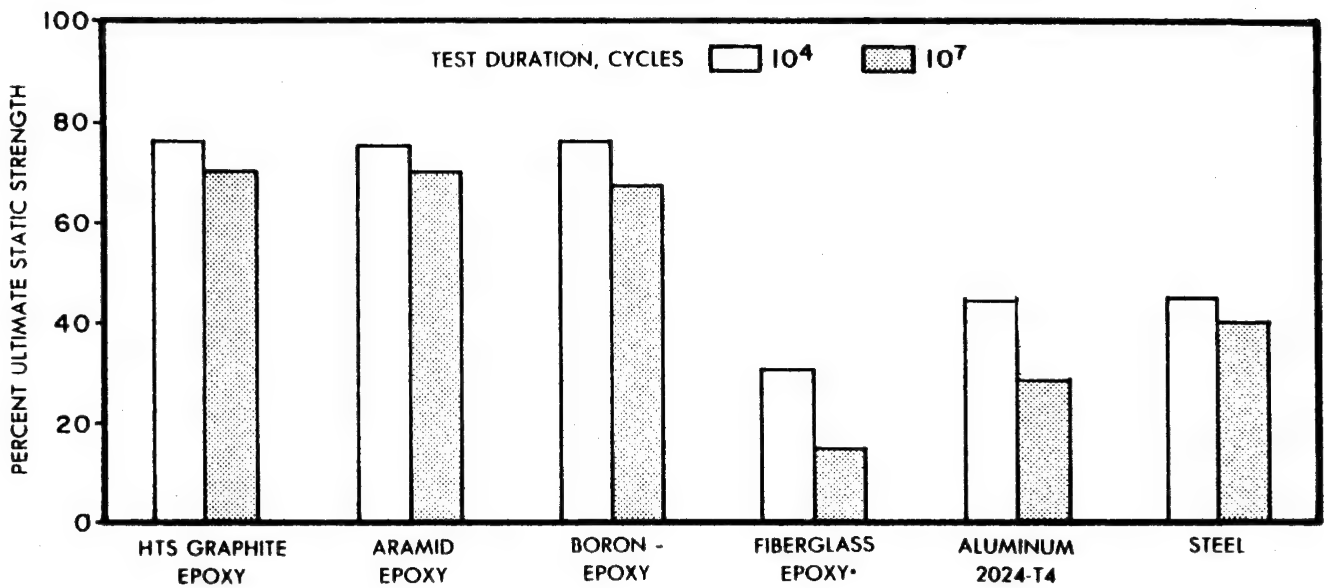


TABLE 2-4

COMPARISON OF MAJOR ATTRIBUTES
OF CURRENTLY AVAILABLE HIGH
PERFORMANCE FIBERS

Fiber	Major Positive Attributes	Major Limitations
Aramid	Highest specific strength High impact strength Low cost	Poor compressive strength Difficult fiber to cut Limited to resin matrix components
Boron	High compressive strength	High cost fiber Low bending radius Not suitable for complex shapes
Silicon Carbide (continuous fiber)	High compressive strength Inert towards molten metals	Low bending radius Relatively high cost
Graphite/Carbon (PAN)	Lowest coefficient of thermal expansion Reasonable Cost Potential Electrical Conductor	Brittle fiber relatively poor impact strength Electrical conductor
Graphite/Carbon (Pitch)	Potentially lowest cost fiber	Low tensile strength High coefficient of variation
Alumina FP	Inert towards molten metals Electrical Insulator Potential low cost	High density resulting in low specific properties

performance fiber. In this aspect, resin matrix composites have the general characteristics of reinforced plastics, metal matrix composites will behave like metals, and so forth.

2.2 FIBER TECHNOLOGY

2.2.1 Introduction

The manufacture and availability of the various high performance filaments that are currently available in the U.S., either in commercial or developmental quantities, are discussed in this section. The list of materials is not very long; there are only three basic filaments offered in commercial quantities (carbon/graphite, aramid, and boron filaments), and only two more being introduced on a developmental basis (silicon carbide and alumina).

There has been extensive work performed to develop high performance fibers from other materials, with varying success. As the demand for composites develops, it is quite likely that new fibers will be made available. However, the identity of the specific fibers that may reach commercial fruition is not clear. Discussion of experimental fiber technology is limited in this report to an exemplary discussion of boron nitride filaments.

2.2.2 Graphite Filaments

2.2.2.1 Introduction

Carbon fibers were first used for electric lamp filaments by Edison in 1880, and carbon fabrics made from graphitized rayon cloth have been available for many years. It is only recently, however, that methods of producing graphitized carbon filaments have been developed that warranted their use as reinforcements in structural composites. Pioneered by the Royal Aircraft Establishment in Great

Britain, filaments of graphitized carbon now are available with strengths approaching 400 Ksi (2800 MPa) or moduli up to 75×10^6 psi (520 GPa).*

2.2.2.2 Manufacturing

Graphitized carbon*, or graphite fibers are made by pyrolitic degradation of a fibrous organic precursor (raw material). In the process, an organic polymeric fiber is heated under tension to very high temperatures in an inert atmosphere to drive off the volatile constituents. The residual carbon atoms orient themselves in a graphite form of carbon of high strength and modulus. Commercially graphite filaments have been made from rayon, polyacrylonitrile (PAN) and pitch fibers. In the 1960's, all the high modulus, high strength graphite produced commercially in the United States was based on a rayon precursor. Its production has been discontinued and at present, PAN based graphite fiber is the predominant commercial product. Pitch base graphite fiber, while being introduced by one manufacturer as a commercial product, is currently viewed as a developmental product.

A simple outline of a graphite process is shown in Figure 2-5.

As outlined in the figure, graphite is formed by passing precursor fibers through a series of controlled ovens. For ease of handling, the fibers are arranged in bundles (tows) which consist of from 1000 to 160,000 individual fibers approximately 12 μm in diameter. The time-temperature history of the fiber establishes the grade of fiber produced: the higher the temperature reached, the higher the degree of graphitization and resulting modulus. However, in general, the strength of the fiber decreases as the module increases. It is possible to obtain many combinations of strength and modulus with graphite fibers. In this

*In this report, the high performance graphitized carbon filaments will be referred to as graphite filaments.

aspect graphite fibers are unlike other high performance fibers which have fixed properties. The fibers, after leaving the oven often are coated with polyvinyl alcohol (PVA) or a resin compatible size to protect the fiber from handling damage. The tows are then wound into spools or woven into cloth or chopped into a mat for further use.

There is significant weight loss during graphitization. From stochiometry considerations, a 45% graphite yield would be expected per unit weight of a PAN precursor. In practice, a lower yield is attained with approximately three pounds of precursor required per pound of graphite produced. A higher yield is obtained with a pitch precursor since pitch has a higher initial carbon content than does PAN.

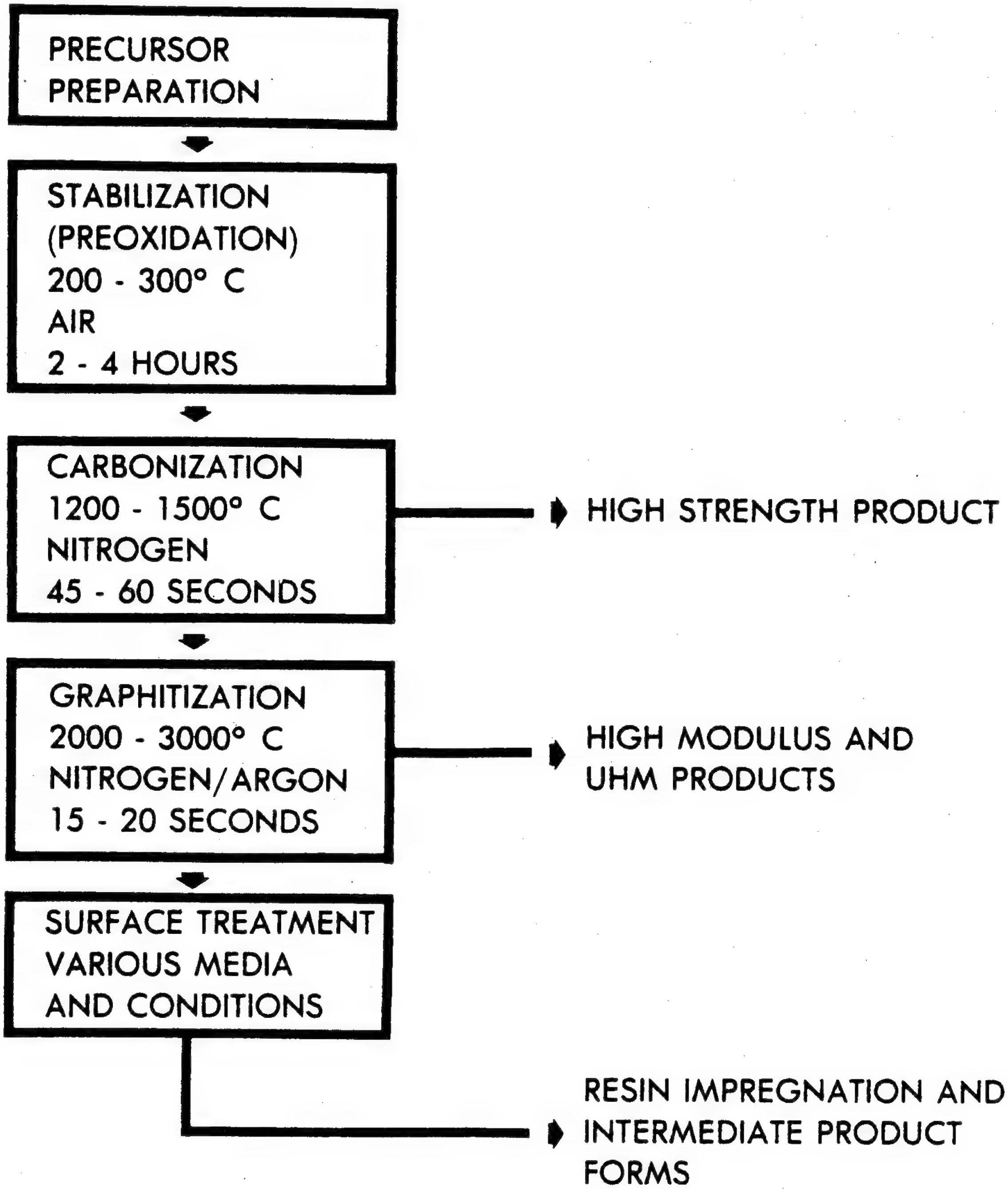
2.2.2.3 Raw Material and Energy Requirements

Graphite filaments are based on petroleum or coal-derived chemicals. PAN precursors used to make graphite are variants of the acrylic and modacrylic fibers commonly used in the textile industry (e.g. Orlon, Dynel). In 1972, 349 million pounds of acrylic and modacrylic fibers were consumed in the U.S. (3). It should be noted that no significant quantities of acrylic filament are currently produced in the U.S. Therefore, PAN graphite consumed in the U.S. at the present, is based to a larger extent on precursors made in other countries, primarily in England and Japan.

Pitch base graphite is based on petroleum or coal tar pitch. Pitch is an inexpensive byproduct of the petrochemical industry similar to tar and is readily available. A fair amount of preparation is necessary to obtain a grade suitable for fiber extrusion.

The principal energy requirement is for electricity consumed in the graphitizing ovens. Current electricity requirements are estimated to be of the order of 20 Kwh/lb of graphite produced. This number is significantly higher than the theoretical energy needed

FIGURE 2-5 GRAPHITE FIBER PROCESS OUTLINE



to form graphite, and reflects inefficiencies of pilot plant scale production. This number is subject to revision, and will decrease with increasing scale of operations.

2.2.2.4 Environmental, Health and Safety Factors

There are a number of potential environmental, health and safety factors associated with the disposal of the volatile products formed during graphitization of the precursor fiber, with the handling of the graphite fiber product, and, in the base of pitch base fibers, in the handling of the precursor raw material.

The volatile products formed during decomposition are noxious and cannot be disposed of in the atmosphere. They have to be eliminated in a secondary operation such as a separate combustor.

Graphite fibers have to be handled carefully. Short lengths of the small diameter fiber can break off and become airborne and be transported by air currents. Graphite fibers are also good electrical conductors. Graphite fibers which settle on electrical contacts or circuits can cause malfunction of electrical and electronic equipment. In order to eliminate this hazard, it is necessary to control ventilation and air flow in areas where graphite fibers are handled, and to shield all electrical equipment in the plant. All electrical equipment must be isolated, or protected by dust proof or explosion proof enclosures.

There is an additional potential hazard associated with the manufacture of pitch base graphite fibers since pitch is a well-recognized carcinogen.

2.2.2.5 Availability of Graphite Fibers

There are five major U.S. distributors of

graphite/carbon fibers at the present time. The types of products sold by these firms are shown in Table 2-5. These fibers are PAN derived except for Union Carbide Corporation's Pitch fiber (Thornel P). Union Carbide and Celanese do not manufacture all the graphite fibers sold under their trademark. Union Carbide's Thornel 300 and Thornel 50 (PAN), and Celanese's Celion fibers are imported from Japan. Union Carbide now only manufactures its Thornel P fiber, but has development facilities for other fibers. These facilities are located in Ohio and South Carolina. The capacity of the pitch plant is rated in "....pounds per hour." (4), or possibly 100,000 lbs/yr (~50 Metric tons/year). Celanese manufactures its high modulus GY70 graphite fiber in a pilot plant associated with the Corporate Research and Development Laboratories in Summit, N.J. This plant has a current capacity of 1000 lbs/month (0.5 metric ton/month) that could be rapidly expanded if required to 30,000 lbs/year (14 Metric tons/yr). Hercules, Inc. manufactures its graphite products in Magna, Utah. Plant capacity has been reported as approximately 100 tons/yr (5). Stackpole's plant capacity has been reported to be 30 tons/year, and Great Lakes Carbon's capacity is reported to be 20 tons/year (5). Avco Corporation's Specialty Materials Division has recently announced that it is building a graphite filaments manufacturing plant that is expected to be in operation by 1979 (6).

2.2.2.6 Current Market for Graphite Fibers

Consumption of graphite fibers in the U.S. has increased from experimental quantities in the late 1960's to approximately 300,000 lbs (140 metric tons) in 1977. A manufacturer's perspective of the historical growth of the graphite fiber market is presented in Figure 2-6. Industry estimates of 1977 consumption range from 250,000 lbs (115 metric tons) to 400,000 lbs (180 metric tons). Over 80% of this material was used as continuous filaments, with the balance being chopped fiber (10%), mat (5%) and cloth (5%). At present, the market for graphite fibers is fairly evenly divided between aerospace and aircraft applications and others. Sporting goods represent the major

TABLE 2-5

PRINCIPAL U.S. SUPPLIERS OF
GRAPHITE FIBERS

Fiber Type	High Strength	High Modulus	Ultra High Modulus
Nominal Fiber Properties			
Tensile strength Ksi (MPa)	~400 (2800)	320 (2200)	250 (1700)
Tensile Modulus Msi (GPa)	30 (220)	50 (350)	70 (500)
Specific Gravity	1.76	1.86	1.96
Distributor			
Union Carbide	x	x (pitch)	x(pitch)
Hercules	x	x	
Celanese	x		x
Great Lakes Carbon Corp.	x	x	
Stackpole	x	x	
Others (Hitco, Avco, imports)			

commercial use of graphite fibers. The estimated market distribution for graphite fibers is currently:

Aerospace and Aircraft	40% - 55%
Sporting Goods	35 - 45
Other Commercial and Developmental Use	balance

These applications will be discussed in more detail in Section 2.4.

The estimated current market share of graphite fibers by supplier is presented in Table 2-6. Union Carbide supplies approximately half the graphite used in this country.

2.2.2.7 Price of Graphite Fibers

The current price of PAN base graphite fiber ranges from \$17/lb to \$250/lb. The price of high strength graphite ranges from \$17/lb for 160,000 filament tow to \$105/lb for 1000 filament tow, with 3000 and 6000 filament tow material selling at \$35/lb and \$32/lb respectively. This price schedule reflects increasing manufacturing costs associated with lower filament tow material. The lower the tow count, the more expensive the raw material from more than \$3.00/lb for low tow count precursor to less than \$1.00/lb for high tow count precursor.

Very high modulus graphite (Celanese GY70) currently sells for \$110/lb to \$150/lb depending on the quantity purchased. The single end grade of this material sells for \$250/lb. Union Carbide's pitch base material currently sells for \$20/lb in fiber form, and \$7.50/lb-\$8.50/lb in mat form.

2.2.2.8 Price Projections

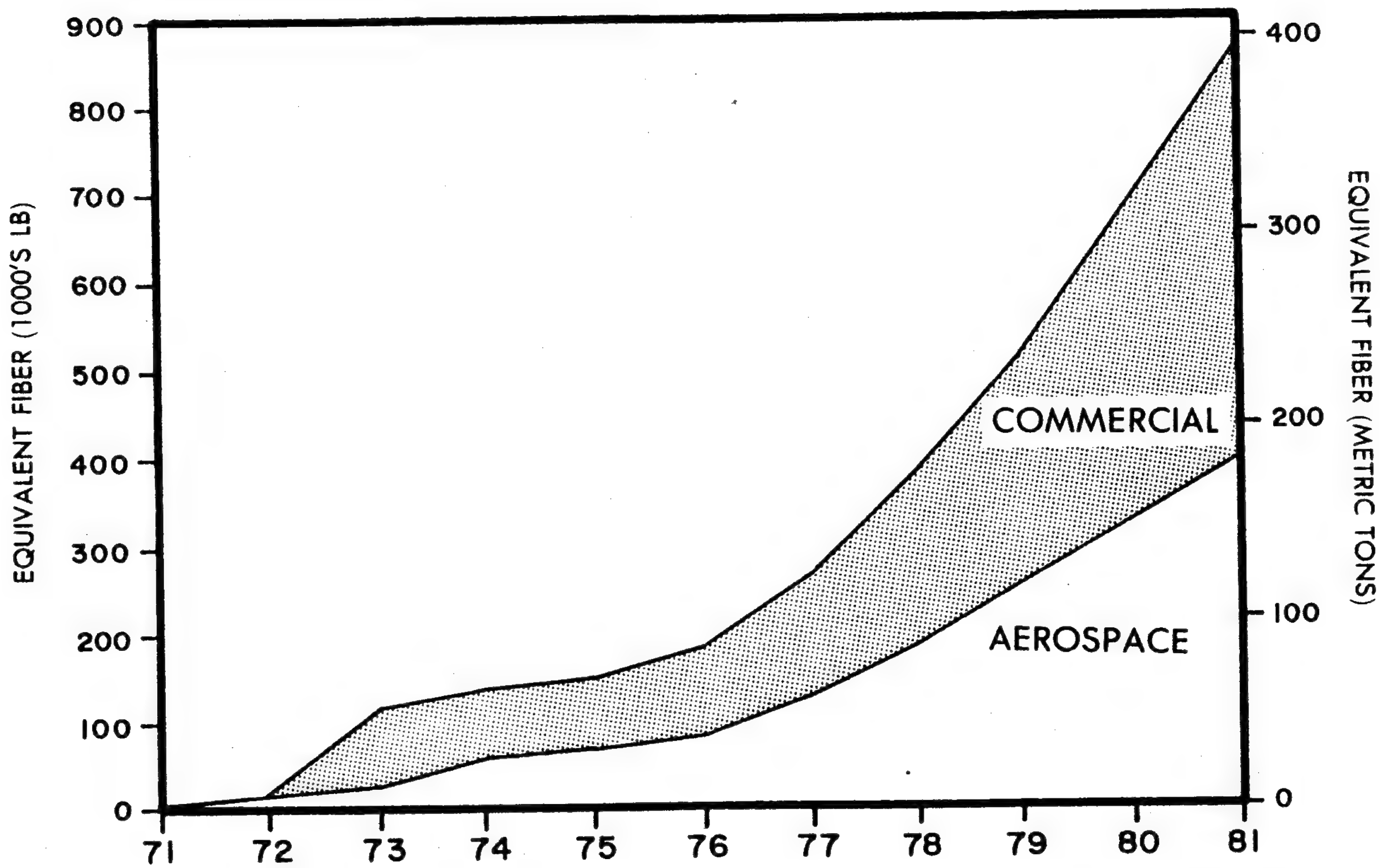
The current price structure of graphite fibers reflects the relatively small current demand for this material. Present

TABLE 2-6

DISTRIBUTION OF GRAPHITE FIBER SALES
BY SUPPLIER

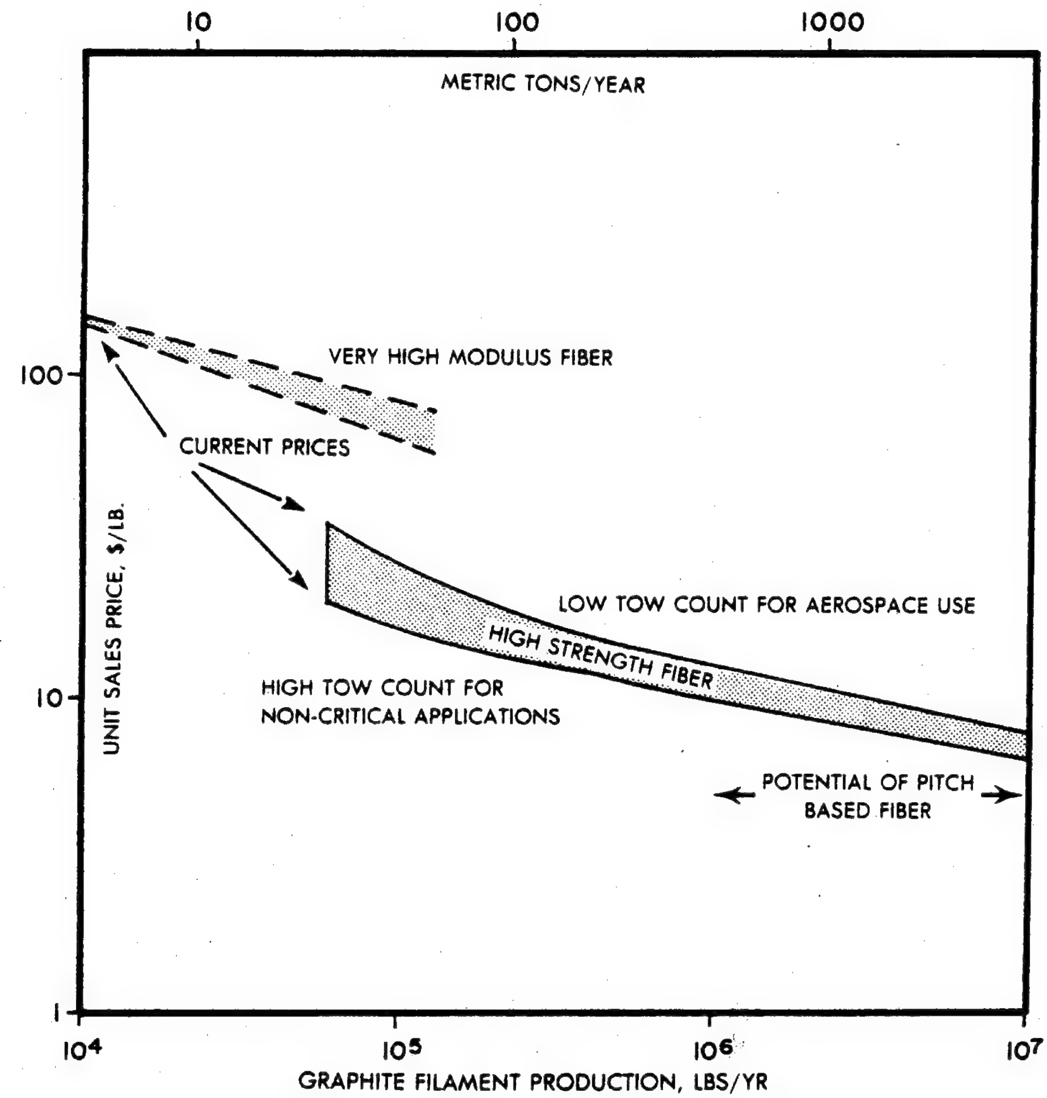
Union Carbide	45–50%
Hercules	20–25%
Celanese	10–15%
Stackpole Carbon	10–15%
Great Lakes Carbon	5–10%
Others (Hitco, AVCO, imports)	balance
Total Current U.S. Market for Graphite Filament	~300,000 lbs/year (140 Mton/year)

FIGURE 2-6 TOTAL GRAPHITE FIBER MARKET



SOURCE:
HERCULES INC.

FIGURE 2-7 PROJECTIONS OF GRAPHITE FILAMENT PRICE AS A FUNCTION OF A MANUFACTURER'S PRODUCTION LEVEL



U.S. demand could be met with one 40 lb/hr plant operating on a round the clock basis. Since the market is divided between a number of suppliers who each produce a number of grades as fibers, production of any one fiber grade is presently only a pilot operation. As a result unit costs and prices are high.

Figure 2-7 presents some price-volume projections obtained from different manufacturers for PAN base graphite. The production volume indicated in this figure is for a particular fiber grade in a single plant. The total market would exceed the indicated production level by a significant amount.

At 200,000 lbs/year (90 metric tons/year), the price of high strength PAN graphite is projected to range from $14/lb for a 40,000 filament tow, to $20/lb for a 3000 filament tow. At a production volume of 10^6 lbs/year (450 M tons/year) the price would range from $10/lb to $13/lb, and at a production volume of 10^7 lbs/yr (4500 M tons/yr) the prices would range from about $6/lb to $8/lb.

High modulus and very high modulus PAN based graphite fiber would be more expensive than the high strength fiber because of higher processing costs. A projected price for very high modulus PAN base graphite fiber is also given in Figure 2-7. This projection is based on current price for the material and the range of slopes presented for the high strength graphite in the same figure.

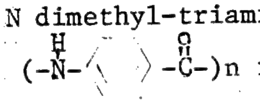
Pitch base graphite fiber could potentially be made available at a lower price than PAN based graphite. Because of the lower cost of the precursor material; less than $1 per pound of graphite for pitch base, as compared to $2 to $10 per pound of graphite for PAN base material. A price of $5/lb for pitch base graphite has been projected if a sufficient (unspecified) volume develops. This projected price is also indicated in Figure 2-7.

2.2.3 Kevlar 49(R) (Aramid) Fiber

2.2.3.1 Introduction

Kevlar(R) is the registered trademark for one member of a family of aromatic polyamide fibers introduced by E.I. du Pont de Nemours & Co., Inc. in 1972. Aramid is the generic name assigned by the Federal Trade Commission to this class of high strength, high modulus organic fibers. Three types of Kevlar fibers are available: Kevlar 49 designed for the reinforcement of plastics, Kevlar 29 designed for ropes, cables and protective clothing, and Kevlar designed for the reinforcement of rubber, especially tires, belts and hoses. Only Kevlar 49 is considered to fall within the scope of the present study.

2.2.3.2 Manufacture

p-Amino benzoyl chloride is polymerized in the presence of N,N dimethyl-triamino phosphate. The resulting polymer, Poly-p Benzamide,  is then spun at a temperature above 500^{o} F ($260^{o}C$) to form Kevlar 49 fibers.(7) Manufacturing details were not available. It is presumed that the manufacturing equipment and process are similar in many respects to the manufacture of other more common polyamide fibers, such as nylon 6, except for the choice of raw materials and operating temperature, and extent of fiber orientation.

2.2.3.3 Raw Materials and Energy Requirements

No specific information was obtained on the availability of p-amino benzoyl chloride or of N,N dimethyl-triamino phosphate, nor on the energy requirements of Kevlar 49 fiber fabrication process. The ultimate raw materials for Kevlar are benzene and methane, two basic petrochemicals.

2.2.3.4 Environmental Constraints

It is presumed that the manufacture of Kevlar 49 fibers presents the same general class of environmental constraints as the manufacture of other polyamide fibers.

2.2.3.5 Availability of Aramid Fibers

Du Pont manufactures its Kevlar products in Richmond, VA. The current plant capacity for all types of Kevlar fibers is 10 million lbs/yr (4500 Metric tons/year). Facilities, which will increase capacity by 50%, are under construction, and will be on stream in 1979 (8).

Distribution of product output is currently as follows:

Kevlar	(tire cords)	80%
Kevlar 29	(cordage)	12-15%
Kevlar 49	(reinforcements)	5-8%

an equivalent current annual capacity for Kevlar 49 is thus approximately 225 to 350 Metric Tons.

Depending on future market needs, total annual capacity for Kevlar products could be expanded from 40 million lbs to 70 million lbs (18,000 to 33,000 Tons) in the next decade. The next round of plant expansion could occur as early as 1982. Product distribution would not be expected to change significantly.

2.2.3.6 Price of Kevlar 49 Fibers

The current price of Kevlar fibers range from \$4.50/lb for chopped fiber to \$27/lb for fine, 200 denier filament. Most grades of Kevlar-49 used for reinforcement range from \$8/lb to \$10/lb. The price structure is considered stable and no further economies of scale

are foreseen with increasing production levels.

2.2.3.7 Current Market for Kevlar 49 Fibers

Consumption of Kevlar 49 fibers in the U.S. has increased from experimental quantities in 1972 to a minimum of approximately 500,000 lbs (225 Metric tons) in 1977. At present the market for Kevlar 49 is distributed as follows:

Boats and Marine Applications	40%
Aerospace and Aircraft	40%
Miscellaneous	20%

2.2.4 Boron Filaments

2.2.4.1 Introduction

In 1959, C. P. Talley of Texaco Experiments, Inc. reported for the first time the high strength and stiffness of boron formed by chemical vapor deposition. The potential of such a material for advanced aircraft applications was recognized by the Air Force Materials Laboratory which funded a large scale research and development effort to advance the filament from the laboratory stage to production level. Boron was the first available continuous reinforcement for light weight high performance composites.

2.2.4.2 Manufacturing

Boron fibers are made in continuous form by reducing boron trichloride with hydrogen and depositing the elemental boron formed on an electrically heated, continuously moving tungsten substrate (0.0005 in. diameter wire). The reaction occurs in a glass deposition tube which is fitted with gas inlet and outlet pools, two mercury filled electrodes, a variable DC power supply connected to the two electrodes, a tungsten substrate let-off system and a boron filament take up unit (9).

A stoichiometric mixture of boron trichloride and hydrogen is introduced at the top of the reactor. These react at the surface of tungsten wire which is heated to a maximum temperature of 1300° C to form a mantle of deposited boron according to the following reaction

$$B\ Cl_3 + 3/2\ H_2 \rightarrow B + 3\ H\ Cl$$

Exhaust gases consisting of HCl, unreacted H_2, BCl_3 and intermediate species are removed through the reactor port at the bottom of the reactor. Typical diameter of the filament exiting the reactor is 0.004 in. (0.010 cm), 0.0056 in. (0.014 cm) or 0.008 in. (0.020 cm), depending upon the drawing rate. A typical reactor produces about 90 lbs (40 kg) of boron per year.

The exhaust gases from the many glass reactors in a boron plant are manifolded for reprocessing. Unreacted boron trichloride is recovered by condensation by refrigerating the gas stream. The residual gases are then sent to a caustic scrubber to remove the acidic vapors (HCl, unrecovered BCl_3, etc.). The resulting brine is then disposed of. Current industry practice is to vent the scrubbed hydrogen to the atmosphere. It would become economically feasible to recycle the hydrogen at higher production volumes.

Boron can also be made by deposition on a carbon monofilament substrate. Replacing the tungsten core by a carbon core reduces the density of the filament by 10%, and there is an added advantage with carbon substrate in that the rate of boron deposition is increased by 30%.

2.2.4.3 Raw Material and Energy Requirements

The principal raw materials for the manufacture of boron fibers are tungsten wire, boron trichloride and hydrogen gas. The fine diameter tungsten wire on which boron is deposited is an imported product and is quite expensive, viz., \$2.50/1000 meters, which is equivalent to about \$500/lb.

Boron trichloride is made in the U.S. by one supplier, Kerr-McGee, in Henderson, Nevada. The current price of this material is \$2.50/lb. Approximately 14-15 lbs (7 Kg) of BCl_3 are needed per pound of boron. Approximately 1000 SCF of hydrogen gas are needed per pound of boron produced. With recycle, however, the consumption would decrease by an order of magnitude.

Based on a current annual production rate of 40,000 lbs (80 Metric Ton) raw materials availability is not a problem. Tungsten requirements represent 1/40% of the current U.S. consumption of tungsten product. Boron trichloride production is limited by the current market for this material, and not by the raw materials, borax and chlorine, both of which are plentiful. Annual hydrogen requirement for the industry are about 40×10^6 SCF or 240,000 lbs (110 Metric Tons). This quantity of hydrogen could be made from approximately two freight car loads of coal by the following overall reaction:

$$\underset{\text{Coal}}{(CH)} + 2H_2O \rightarrow CO_2 + 2.5\ H_2$$

2.2.4.4 Environmental, Health and Safety Factors

The boron process is a clean self-contained process and does not present any major environmental, health, or safety hazards, except for the use of mercury in the reactor electrodes. The principal hazard presented by a boron plant would be associated with accidental leakage of either the reaction gases into the atmosphere, or of air into the system. BCl_3 and HCl are noxious gases, and hydrogen can explode.

2.2.4.5 Availability of Boron Fibers

There are two producers of boron fibers in the U.S. at the present time. Avco Corp. has a 35,000 lb/yr (16 metric tons/yr) plant in Lowell, MA. Composite Technology, Inc. (CTI) has a 10,000

lb/yr (5 metric ton/yr) plant in Broad Brook, CT.

Both manufacturers offer 4 mil, 5.6 mil and 8.0 mil boron fiber with a tungsten core. CTI also offers for sale a 2.2 mil boron-tungsten fiber as well as a "Borsic"(R) tungsten fiber in 2 sizes, 5.7 mil and 8.2 mil in diameter. Borsic is a boron fiber with a silicon carbide outer shell (see silicon carbide sections). A small fraction (10) (less than 10%) of Avco's current production capacity is boron on a carbon substrate.

2.2.4.6 Current Market for Boron Fibers

The current demand for boron fibers is approximately 32,000 lb/yr (15 metric ton/yr) with the following market distribution

Military Aircraft	81%
Sporting Goods	13%
Miscellaneous Other Applications (Aerospace and commercial)	6%

This market is shared by Avco and CTI in an 80/20 ratio.

2.2.4.7 Current Price of Boron Fibers

The prices of the types of boron fiber that are currently available are summarized in Table 2-7. The price of boron on tungsten fiber decreases significantly with increasing fiber diameter. This is principally due to the significant decrease in the weight fraction of tungsten in the fiber with increasing diameter. There are variations in price between fiber certified for aerospace applications, and commercial grade fiber which is similar to aerospace grade except that the manufacturing control and testing requirements are less stringent.

As of yet there is no standard price established for boron on carbon fiber which is quoted on an individual order basis.

TABLE 2-7

Current Price of Boron Fibers

Fiber Type	Diameter mil.	Sales Price $/lb
Boron/tungsten	2.0	500
	4.0	240
	5.6	180-220
	8.0	170-200
Borsic/tungsten	5.7	350
	8.1	350

The price is claimed to be competitive with boron on tungsten fiber.

2.2.4.8 Price Projections

The current price of boron is determined by both high raw material costs and high capital costs associated low production output. The current cost structure for the manufacture of 5.6 mil boron on tungsten fiber is presented in Table 2-8. Capital costs are estimated to be $2,000,000 for a 9000 lb/yr (4 metric tons/year) plant, or $220 per annual pound. The estimated total costs are about 15% less than the current mean price of $200/lb for 5.6 mil boron. The 15% difference is a reasonable allowance for costs of sales and profit margin.

The cost structure for a plant with a projected capacity of one million pounds per year is presented in Table 2.9. The capital cost assumed for this plant, $50/annual pound (current dollars), is based on conversations with Avco and CTI (11, 12). The plant design includes a hydrogen recycling capability. It is also further assumed that carbon monofilament substrate would be used instead of tungsten fiber. The cost of carbon substrate is based on projected cost of high strength aerospace graphite filament produced at a rate of 100,000 lbs/yr. No price reduction for boron trichloride is assumed. This could change if more than one supplier became available. Labor requirements were assumed to be half current ones.

Total operating costs are estimated to be $74/lb of boron or 43% of current costs. At this cost level, boron filament would be priced at between $85/lb and $90/lb. This price is significantly higher than the price of aramid or graphite fibers at the same production level.

TABLE 2-8

Current Manufacturing Costs of 5.6 Mil Boron on Tungsten Fiber

Production Rate lbs/yr	9000
Capital Investment, $\$10^6$	2.0

Operating Costs

Item	Units/lb Boron	Unit Costs	Cost $/lb Boron	
Boron Trichloride	14 lbs	$2.50/lb	35	
Hydrogen	1000 SCF	$10/1000 SCF	10	
Tungsten Substrate	38000ft	$\$2.50/10^3M$	29	
Other Chemicals & Supplies			2	
Electric Power	100 kWh	4¢/kWh	4	
Sub-total - Materials and Energy				80
Direct Labor	1 man-hour	8.00/man-hour	8	
Overhead and Supervision	100% Direct Labor		8	
Sub-total - Labor and Supervision				16
Depreciation (5 year)			44	
Interest	10% capital investment/year		22	
Maintenance	6% capital investment/year		12	
Sub-total - Capital Related Charges				78
Total Operating Costs				174

TABLE 2-9

Projected Manufacturing Costs of 5.6 Mil
Boron on Carbon Fiber

Assumed Production, lbs/yr	10^6
Capital Investment $\$10^6$	50

Operating Cost

Item	Units/lb Boron	Unit Costs	Cost $/lb Boron	
Boron Trichloride	14 lbs	$2.50/lb	35	
Hydrogen	100 SCF	$\$10/10^3$SCF	1	
Carbon Substrate	0.1 lbs	$30/lb	3	
Other Chemicals & Supplies			2	
Electrical Power	100 kWh	4¢/kWh	4	
Sub-Total Materials and Energy				45
Direct Labor	0.5 man-hour	8.00/man-hour	4	
Overhead and Supervision	100% Direct Labor		4	
Sub-Total Labor and Supervision				8
Depreciation (5 year)			10	
Interest	10% Capital Investment/year		5	
Maintenance	6% Capital Investment/year		6	
Sub-Total Capital Related Charges				21
Total Operating Costs				74

2.2.5 Silicon Carbide Fibers

2.2.5.1 Introduction

Silicon carbide is available in continuous filaments and as whiskers. Silicon carbide (SiC) filaments were originally developed by General Technology Corp. in 1966 under contract to the Air Force Materials Laboratory. SiC filaments are made by chemical vapor deposition in the same manner as boron. The original impetus for developing SiC filaments was to obtain a fiber better-suited than boron for incorporation in metal matrix composites. Boron rapidly loses its strength at temperatures above 1000°F, and is not suitable for high temperature applications. Furthermore, boron reacts with molten metals, such as aluminum, which makes the fabrication of metal matrix composites by liquid infiltration or standard casting techniques not feasible. Silicon carbide filaments retain their mechanical properties at temperatures well over 1000° F and can withstand exposure to molten aluminum.

Subsequently, it was noted that silicon carbide filaments could be potentially less costly to manufacture than boron filaments of similar properties. Economics are the current driver behind the support of silicon carbide technology.

A variant product is "Borsic"(R) which is made by depositing an outer layer of silicon carbide over a boron filament.

2.2.5.2 Manufacturing

Silicon carbide (SiC) filaments are made in continuous form by decomposition of methylchloro-silanes on a heated substrate in the present of hydrogen, in the same manner and equipment as are used to make boron fibers. SiC filaments have been made on both tungsten and carbon substrates. The deposition rate of SiC is higher than that of boron because of a faster rate of reaction and because the

specific gravity of SiC (3.1) is higher than that of boron (2.4). It is estimated that a single reactor can produce 150 lbs/yr of SiC filament.

2.2.5.3 Raw Material and Energy Requirements

The raw material requirements are the same as those for boron, except that methylchlorosilanes are used instead of boron trichloride. Methyl chlorosilanes are common chemicals currently used to make silicones and organic silanes. The current price of methyl dichlorosilane is less than $1/lb. Because of the higher molecular weight of SiC as compared to boron, only approximately 5 lbs of methyl dichlorosilane are required per pound of silicon carbide produced.

There is no theoretical requirement for hydrogen to form silicon carbide; however the quality of SiC obtained is much improved if the decomposition of the silicon occurs in the presence of hydrogen. In small scale production, hydrogen consumption is the same as that of boron. In large scale production, hydrogen could be recycled essentially completely and its consumption would be limited by recycle venting requirements.

Energy requirements are lower than those needed for boron because of the higher production rate. It is estimated that 60 kWh of electricity are needed per pound of silicon carbide fiber produced.

2.2.5.4 Availability of Silicon Carbide Filaments

Avco Corp. in Lowell, Mass. is the only U.S. producer of silicon carbide fibers. Avco can currently produce 150 lbs/year (70 kg/year) of either 4.0 mil or 5.6 mil fiber. It is currently expanding its facilities to be able to produce 500 lbs/yr (220 kg/yr). A similar material is being made in West Germany by the Berghof Research Institute, which is represented in the U.S. by Fiber Materials Inc. of Biddeford, Maine. A different type of silicon carbide filament is also manufactured in Japan by Nippon Carbon on a developmental basis.

If the market for silicon carbide develops, a facility similar to Avco's existing boron plant would be able to produce 75,000 lbs/year (35 metric tons/year) of silicon carbide.

2.2.5.5 Current Market for Silicon Carbon Filaments

There is no established market for silicon carbide at the moment.

2.2.5.6 Current Price of Silicon Carbide Filaments

The current price of silicon carbide filament is $450/lb.

2.2.5.7 Price Projections for Silicon Carbide Filaments

The current price of silicon carbide reflects its developmental status. Cost of production and price would drop as the fibers are made in larger volumes. the projected costs for silicon carbide on tungsten substrate at 15,000 lbs/year production rate are given in Tables 2-10 and 2-11. These tables are based on the information given in Tables 2-8 and 2-9, with adjustment for differences in raw materials and production rates. At a production rate of 15,000 lbs/year, it is estimated that silicon carbide would cost $96/lb to produce. This is 55% of the cost of boron of an equivalent weight basis, or 68% of the cost of boron on an equal volume basis. At that production level, silicon carbide fibers would sell for about $110-$130 per pound. At a production rate of one million pounds per year, the estimated cost of silicon carbide on carbon would drop to $26/lb. This is 35% of the cost of boron on an equal weight basis at the same production level. At this production level, silicon carbide would be expected to sell at a price of $30-$35/lb. This is about three times the projected price of graphite fibers and about twice the projected price of FP-alumina fibers (see next section) at the same production level. Per unit volume of material,

TABLE 2-10

Projected Low Volume Manufacturing Costs of 5.6 Mil Silicon Carbide Filaments on a Tungsten Substrate

Production Rate lbs/yr (Kg/yr)			15,000	(7,000)
Capital Investment $\$10^6$			2.0	

OPERATING COSTS

Item	Units/lb SiC	Unit Cost	Cost $/lb SiC	
Methyltrichlorosilane	5.0 lb	0.80/lb*	4.00	
Hydrogen	600 SCF	$10/MSCF	6.00	
Tungsten Substrate	30,000 ft	$\$2.50/10^3M$	23.00	
Other Chemicals and Supplies			2.00	
Electric Power	60 kWh	4¢/hWh	2.40	
Sub-Total Materials and Energy				37.40
Direct Labor	0.6 manhour	$8/manhour	4.80	
Overhead and Supervision	100% Direct Labor		4.80	
Sub-Total Labor and Supervision				9.60
Depreciation (5 years)			27.70	
Interest	10% capital investment/yr		13.80	
Maintenance	6 % capital investment/yr		8.00	
Sub-Total Capital Related Charges				49.00
Total Operating Costs				$96.00

*assumed

TABLE 2-11

Projected High Volume Manufacturing Costs of 5.6 Mil

Silicon Carbide Filaments on a Carbon Substrate

Production Rate/lbs/yr	10^6
Capital Investment, $\$10^6$	30

Operating Costs

Item	Units/lb SiC	Unit Cost	Costs $/lb SiC	
Methyl trichlorosilane	5.0	$ 0.80/lb	$4.00	
Hydrogen	Trace		-	
Carbon Substrate	0.08 lb	$30/lb	2.40	
Other Chemicals and Supplies			2.00	
Electric Power	60 kWh	4¢/kWh	2.40	
Sub-total Materials and Energy				$10.80
Direct Labor	0.3 manhours	$8/manhr	2.40	
Overhead and Supervision	100% direct labor		2.40	
Sub-total Labor and Supervision				4.80
Depreciation (5 years)			6.00	
Interest (10% capital investment/year)			3.00	
Maintenance (6% capital investment/year)			1.80	
Sub-total Capital Related Charges				10.80
Total Operating Costs				$26.40

silicon carbide fibers would cost about five times as much as the less dense graphite fibers, but only 50% more than the denser FP alumina fibers.

2.2.5.8 Silicon Carbide Whiskers

The pyrolysis of rice hulls, which naturally contain silicon and carbon, has been found to produce particulate silicon carbide. About 10% to 15% of the pyrolysis product consists of SiC whiskers, approximately 1μm to 3μm in diameter, that have length to diameter ratios in excess of ten. These whiskers should be suitable as discontinuous reinforcements for either metal matrix or resin matrix composites. Work is currently under way to increase the whisker yield. Whisker concentrations in excess of 30% have been reported (13).

Experimental quantities of SiC whiskers, mixed with particles obtained by the pyrolysis, are currently available from the Silag Division of Exxon Enterprises, Inc., at a price of $250/lb. If large volume demand developed, it is envisioned that the material could be made available at a significantly lower price, of the order of $10/lb at a production volume of a million pounds per year (14).

2.2.6 Alumina Fibers

2.2.6.1 Introduction

E. I. duPont de Nemours and Co. Inc. is currently developing a high modulus inorganic fiber designed as Fiber FP. This material is a continuous filament polycrystalline α alumina yarn. This fiber is being considered principally for high temperature metal matrix applications.

2.2.6.2 Manufacturing

According to the patent literature that has been

issued to date (15, 16, 17) FP alumina fibers are presumed to be prepared by extruding an aqueous gel of $Al_2(OH)_5Cl$ through spinnerets, drying the resulting fibers to remove most of the water, and then heat treating the filaments under a programmed time-temperature cycle to form a continuous refractory oxide yarn. Maximum processing temperature is 1300°C. The $Al_2(OH)_5Cl$ gel is prepared by reacting finely divided (less than 3 μm diameter) Al_2O_3 particles suspended in water with hydrochloric acid, adjusting the concentration of alumina by distillation and adding small amounts of magnesium chloride to adjust its viscosity. Since hydrochloric acid is formed during the firing of the unsintered fiber, vapors from the furnaces must be sent to a caustic scrubber before being vented.

2.2.6.3 Raw Material and Energy Requirements

The principal raw materials for the manufacture of alumina FP fibers appear to be alumina powder, water, hydrochloric acid and magnesium chloride, all of which are commonly available materials.

The principal energy requirements in the process are associated with the heating of the green fiber to elevated temperature to form polycrystalline alumina, and with the evaporation of water originally used to slurry aluminum oxide powder to form the aluminum hydroxide gel.

Theoretical energy refinements for these two steps are estimated to be approximately 950 cals/gram Al_2O_3 for firing and 250 cals/gram Al_2O_3 for evaporation (assuming a 30 weight percent water content in the slurry), or a total of 1200 cals/gram Al_2O_3. Assuming a 30% energy utilization efficiency, approximately 3.6 Kcals of energy (as fossil fuel) are required per gram of Al_2O_3 produced. The above neglects power required to extrude and handle the fibers.

2.2.6.4 Environmental, Health and Safety Factors

Based on available information, the manufacture of FP alumina fibers should be a clean self-contained operation that should not present any major environmental, health, or safety hazard.

2.2.6.5 Availability of Alumina FP Fibers

At the present time, alumina FP fibers are only made in pilot quantities at a prototype facility at the duPont Experimental Station in Wilmington, DE. With some modification, this facility could produce up to 30,000 lbs/yr (13 metric tons/yr). At present, two types of fiber are available: pure alumina, and alumina coated with silica for resin and non-metal applications.

2.2.6.6 Current Market for Alumina FP Fibers

There is no established market for alumina FP at the moment.

2.2.6.7 Current Price of Alumina FP Fibers

The current price of standard alumina FP fiber yarn is $200/lb.

2.2.6.8 Projected Price of Alumina FP Fibers

The current price of alumina FP fibers reflects the developmental status of this material. Cost of production and price would drop as the fibers were made in large quantities. DuPont's price-volume projections are given in Table 2-12 (18).

2.2.7 Boron Nitride Fibers

Current development activities by the Carborundum Company

TABLE 2-12

Price Volume Projections
for Alumina FP Fibers

Manufacturing Facility	Plant Output lbs/yr	Price FP Fiber $/lb
Pilot Plant	current	200
Pilot Plant	30,000	60
Production Plant	500,000	28
Production Plant	1,000,000	18
Production Plant	5,000,000	8

Source: Reference 18.

in Niagara Falls, N.Y. may result in a boron nitride fiber that could be commercially important in a few years. Boron nitride fiber is prepared in two steps. Boron oxide precursor fibers are first prepared by conventional melt spinning techniques used in the manufacture of standard glass fibers. The boron oxide fiber is converted to boron nitride (BN) by reaction with ammonia at elevated temperature (>1500^{o}C). The reaction is slow and is limited by the diffusion of ammonia into the solid fiber. Since the two raw materials, ammonia and boron oxide, used to make the BN fibers are commodity chemicals and since the process makes use of existing fiber glass drawing technology, the projected costs for large scale boron nitride manufacture could be quite low; higher than for fiber glass, but lower than for any of the other high performance fibers currently being used.

Representative BN fiber properties that are currently achieved are presented in Table 2-2.

The development is still at an exploratory level, and boron nitride fibers are currently being made on an experimental basis in gram quantities. The properties of the fibers have been found to vary significantly from sample to sample, a single fiber may have significantly higher or lower properties than the average presented in Table 2-2. Individual fibers have been prepared that have a tensile strength of 340 Ksi (2350 MPa) and a modulus of 41 x 10^6 psi (280 GPa), values comparable to those of a high strength graphite filament. Boron nitride fibers also have about the same density as graphite fibers. The filaments differ in that boron nitride does not conduct electricity and does not react with molten metals. The current program goals are to make high strength and modulus BN fibers on a reproducible basis. A pilot plant would then be installed, so that kilogram quantities of fibers could be made available for evaluation (19). The company is also developing relatively low strength, low modulus boron nitride chopped fiber for use as separator matrix material in lithium sulfide batteries.

2.3 FABRICATION OF ADVANCED COMPOSITES

2.3.1 Introduction

Advanced composites have been made with a wide variety of matrix materials. These include many thermosetting and thermoplastic resins, carbon, metals, and even ceramics and glass. The status of each of the first three classes of composites will be reviewed in turn. Plastic resins have been the predominant matrix materials used to make advanced composites to date, and most of the current production applications of advanced composites use resin matrix systems. A major reason for the predominance of resin matrix systems, as compared to metal matrix systems, for example, is that much of the fabrication technology developed for fiberglass reinforced plastics was directly applicable, or at least adaptable, to the fabrication of advanced composite systems.

2.3.2 Organic Matrix Composites

2.3.2.1 Matrix Materials

The manufacture of plastic resins for incorporation in fiber reinforced plastics is a major industry, as shown in Table 2-13. The combination of thermosetting unsaturated resins with glass fibers accounts for the bulk of reinforced plastics products.

Thermosets are those resins which in the presence of a catalyst, heat and/or pressure undergo an irreversible chemical reaction (cure). Prior to cure, thermosets may be liquid or made to flow under pressure and thus can take on a desired form. Once cured, they cannot be returned to the uncured state, or reshaped.

Phenolics, epoxies, vinyl esters, and fumarate resins bring thermosets' share of the market to 90%. The thermoplastics, which account for the remainder, in general relative importance are

TABLE 2-13

U.S. 1977 Reinforced Resin Consumption

	In Reinforced Plastics	Total Consumption
	←1000 metric tons→	
Thermosetting Resins		
Epoxy	22	125
Phenolic	41	638
Polyester Unsaturated	370 (700[a])	477
Urea-Melamine	15	514
	448	1754
Thermoplastic Resins		
Nylon	17[(a)]	110
Polyacetal	2[(a)]	42
Polyester, Thermoplastic	15[(a)]	21
Polyethylene, H.D.	2[(a)]	1620
Polypropylene	30[(a)]	1247
Styrenics[b]	13[(a)]	2110
Other[c]	9[(a)]	150
Total	88[(a)]	5300

a) includes reinforcement material

b) Polystyrene, ABS and SAN

c) includes Noryl, polycarbonate, polysulfone, fluroplastics, polyphenylene sulfide, etc.

Source: Reference 20

polyolefins, nylon, thermoplastic polyesters, styrenics, and a variety of engineering thermoplastic resins, such as acetal, polycarbonate, polyphenylene sulfide, and polysulfone.

Thermoplastics are normally solids at room temperature that can be softened or melted by heat, made to flow under pressure, and which reharden by cooling. The cycle can be repeated thereby enabling their reuse.

High performance fibers can be combined with most of the conventional thermosetting and thermoplastic resins quite successfully, often with no special fiber finish (or size) being required. Key properties of the principal resin systems that have been used to make advanced composites are summarized in Table 2-14. Historically, high performance, high cost resin systems have been used in advanced composites. Because of the much higher cost of the incorporated fibers, the cost of even an expensive resin (e.g. $10/lb or more) did not contribute significantly to the total cost of the composite. As the price of the filaments decreases, however, the cost of the resin becomes proportionally more important, and a greater emphasis is now being placed on low cost resin systems (less than $1/lb) that are easy to process, even though these systems may not equal the performance characteristics of the more expensive resins.

Epoxy resins have been the predominant matrix material for advanced composites. Two classes of epoxy resins have been used: high temperature resins which retain their mechanical properties at $350^{\circ}F$ ($176^{\circ}C$) and the general purpose resins which can be used at temperatures of up to $180^{\circ}F$ ($82^{\circ}C$). The high temperature grades are principally used in aerospace applications, whereas the general purpose resins are principally used in commercial applications which find principal use at ambient temperature. The general purpose resins are significantly less expensive than the high temperature resins, and also are easier to process, both in terms of lower cure temperature, $200^{\circ}F$ ($90^{\circ}C$) vs. $400^{\circ}F$ ($200^{\circ}C$),

TABLE 2-14

Resins Used as Matrices in Advanced Composites

Resin		Epoxy	Phenolic	Polyester (Rigid)	Poly-imide	Nylon 6-6	Poly-sulfone	Polyaryl Sulfone	Polyether Sulfone	Polyphe-nylene Sulfide	Poly-Amide/ Imide
Property	ASTM Test Method	THERMOSETTING RESINS				THERMOPLASTIC RESINS					
Specific Gravity	D 792	1.1-1.4	1.25-1.30	1.10-1.46	1.37	1.14	1.24	1.36	1.37	1.34	1.40
RT Mechanical Properties											
Flexural Strength Ksi	D 790	13-21	12-15	8.5-23	19	15.0	15.4	17.2	18.7	20	30.7
Flexural Modulus Msi	D 790				0.6	0.4	0.4	0.4	0.4	0.6	0.6
Tensile Strength Ksi	D 638	4-13	7-8	6-13	12	12	10	13	12	10	27
Tensile Modulus Msi	D 638	0.4-0.6	0.7-1.0	0.3-0.6	0.6	0.5	0.4	0.4	0.4	0.5	0.7
Distortion Temperature @ 264 psi, °F	D 648	115-550	240-260	140-400		150	345	525	397	275	525
Resistance to Heat Continuous Exposure, °F		250-500	250	250	>600	180	300	500	300	400-500	>650
Flammability	D 635	slow	very slow	Burns to self extin-guishing	Self extin-guishing	Self extin-guishing	Self extin-guishing	Self extin-guishing	Self extin-guishing	Non-burning	Self extin-guishing
Representative Cure/ Molding Conditions											
Temperature		250-450	270-360	270-350	400-700	520-620	250-325	720-750	610-710	550-675	600-625
Pressure psi			2000-4000	300-1200	2000	variable	100-3000	1000-2000	1000-1500	1000-1500	20,000 (inj. mold)
Price $/lb		0.70 to 10	0.47	0.36 (gen. purpose)	75-100 (cur.) 25(proj.)	1.16	2.95-4.75	20-40	6.50-11.00	2.05	9.75
Suppliers		7	31	19	2	13 (incl. other nylons)	Union Carbide Corp.	Carbor-undum Corp., Plastics Division	ICI America	Phillips Petro-leum Co.	Amoco Chemicals Corp.

and faster cycle time (1 to 2 hours cure cycle vs. 4 to 6 hour cure cycle).

Other resin systems are being extensively examined as candidate matrix materials to achieve two totally different goals. The first is to obtain resin matrix composites that can withstand significantly higher temperatures than the 350°F operational limit of the high temperature epoxies that represent the current state-of-the-art. The leading candidate systems being considered are thermosetting polyimides, such as Thermid 600, manufactured by Gulf Oil Chemicals Company or PMR-15 resin developed by NASA Lewis Research Center. The polyimide resins are currently expensive (up to $100/lb), and difficult to cure, with high pressures (up to 2150 psi), high temperatures (up to 700°F) and long cycle times (2 hour mold time with 16 hours post cure) being required. However, these resins allow composites to be considered for aerospace applications which now normally use titanium as a material of construction.

The other major thrust is to lower significantly the costs of composites. This entails using resin systems which in themselves are significantly cheaper than the epoxy resins, and which also lend themselves to lower fabrication costs. Thermosetting polyesters are now being extensively examined as candidate matrix materials for mass production applications of advanced composites. As shown in Table 2-13, unsaturated polyesters are the matrix material of choice in the myriad consumer applications of fiberglass reinforced plastics. While the polyesters do not exhibit all the mechanical properties of the higher performance engineering plastics, they are significantly less expensive (36¢/lb for general purpose resin). Furthermore polyester formulations currently exist that cure rapidly (in minutes or less) and therefore are amenable to high speed, mass production fabrication methods.

There is also interest in thermoplastic resins, that exhibit reasonably high temperature resistance as composite matrices. These thermoplastic resins lend themselves to rapid processing and to post-forming which can result in significant cost reductions in the

manufacture of complex parts. These thermoformable resins can be reprocessed, which can result in a lower reject rate. This property also has implications in terms of the recycling of either industrial or post-consumer scrap composite parts.

2.3.2.2 Mill Products (Pre-Combining Methods and Composites)

In the rationalization of the fiber reinforced plastic industry, it has become fairly standard practice to treat the blending of fiber and resin as a distinct operation separate from the fabrication or molding of the fiber reinforced plastic component. The precombining methods or compounds used depend on the type of resin and fabrication method used. Of the many methods available, resin preimpregnation (pre-preg), sheet molding compound (SMC), and thermoplastic compounding are most commonly applied to the fabrication of advanced composite parts. These intermediates are considered analogous to the mill products (sheet, rod, and bar stock) of the metallurgical industry.

<u>Thermoset Preimpregnated (Pre-preg) Products</u>: "Pre-preg" is a preformulated mixture of fibers and partially cured resin that requires no further processing other than cutting to shape, laying up in the mold and curing under a specified time, temperature-pressure cycle. These intermediate materials are formulated to take the chemistry out of production operations.

Non-woven unidirectional pre-pregs are made by wetting parallel strands of fibers in a resin tank, passing the impregnated fibers through a set of doctor blades to control resin content, collimating the filaments on a paper substrate, and then advancing the materials through controlled ovens to drive off volatiles. The resulting "B stage" material is a relatively dry, tack-free material that is relatively easy to handle. A distinction is made between narrow prepreg (less than 3 in. (7.5 cm) wide) and prepreg broad goods which can be as wide as 48 in. (120 cm). If the fiber can be woven, an alternative form of pre-

preg is obtained by drawing a fibrous cloth through the impregnating resin solution. Except for the fabrication of filament wound parts, use of prepregs is currently the standard mode of operation in the advanced composite industry. A list of the major suppliers of advanced composite prepregs is given in Table 2-15.

While "pre-pregs" offer many advantages to the manufacturer of a final composite part, there are certain inherent disadvantages associated with them. First and foremost is that all prepregs have a finite shelf life that is temperature dependent. Typical shelf lives for epoxy matrix prepregs are 6 months at $0^{\circ}F$ ($-18^{\circ}C$) or 14 days at $70^{\circ}F$ ($21^{\circ}C$). Use of prepregs requires refrigerated transportation from the prepregger to the manufacturer of the composite part, and refrigerated storage facilities in the manufacturer's shop. Furthermore, raw material inventory has to be carefully maintained and rotated to prevent waste due to spoilage of average stock. Prepreg removed from storage also must be thawed prior to processing. All these requirements add to the cost of the final product.

A second limitation to using prepregs is that each prepreg on the market is unique. For example, the various prepreggers all offer a unidirectional graphite, high temperature epoxy prepreg. The properties of the composites produced from these various systems are generally comparable; however, the fabrication cycle varies from prepreg to prepreg. It is, furthermore, not generally possible to mix different prepregs in the lay-up of a composite part. For example, while Fiberite's 934 epoxy resin system, Narmco's 5208 resin system, and Hercules' 3501-5 resin system are all rated for $350^{\circ}F$ ($176^{\circ}C$) service, they are separate and distinct formulations that differ chemically and may not be amenable to co-curing, i.e., to fabrication in a single heating cycle. This is of concern to many of the current and potential manufacturers of composite parts. Most firms consider multi-source availability of any purchased material as a fundamental tenet of good business practice. Since prepregs can be incompatible, although this situation has not proven

TABLE 2-15

List of Representative Prepreggers

Avco Corp.(*) Specialties Material Division Lowell, MA	Fiberite Corp. Winona, MN
Hercules Inc.(*) Systems Group Magna, UT	Hexcel Corp. Dublin, CA
Narmco Materials Inc. Subsidiary of Celanese Corporation(*) Costa Mesa, CA	3M Corp. Industrial Specialties Div. St. Paul, MN

*Integrated Fiber Supplier

to be a major obstacle to the introduction of composites in industry, the lack of manufacturing compatibility of prepreg formulations is a demuring factor. Federal agencies, such as AMMRAC, and the major aerospace manufacturers are developing physico-chemical methods of characterizing epoxy resins that are sufficiently detailed so that in the future the resins can be specified generically, and thus eliminating the proprietary aspects of current specifications.

A last drawback to the prepregs is that they are expensive. Current prices for various prepregs are given in Table 2-16. In general, the price of prepregs is significantly more than the price of the raw materials that go into their formulation. A rule of thumb in the industry is that the price of a unidirectional prepreg per unit weight is roughly equal to the price of the fiber per unit weight. For example, the price of one pound of boron/epoxy tape is about $200/lb, which compares with the price of one pound of boron filament although the tape contains only 2/3 lb of boron. Cloth prepregs are more expensive (currently $80-100/lb for a high strength graphite-epoxy prepreg).

Sheet Molding Compounds: Sheet molding compound (SMC) technology is currently used to make a preform sheet of fiberglass reinforced polyester, which can subsequently be formed into a finished part by compression molding. Polyester formulations currently exist that cure in 1-2 minutes rather than the hours characteristic of epoxy prepregs. The technology is currently used in such as the manufacture of furniture, appliance parts, and automotive components.

SMC is made by depositing chopped fibers 1/2 in. (1 cm) to 2 in. (5 cm) in length or continuous fibers on a layer of resin paste on a carrier film. The fibers are sandwiched by a second paste/film layer, and the resulting product form kneaded under pressure to wet out the fibers. The resulting sheet is wound under tension on a roll and stored until needed.

TABLE 2-16

Representative Unidirectional

Epoxy Prepreg Prices

Resin Matrix	Fiber	Nominal Resin Content Weight-Percent	Price $/lb
High Temperature Epoxy	High Strength Graphite	42	40-60
High Temperature Epoxy	Ultra High Modulus Graphite	42	$180-$200
High Temperature Epoxy	Boron	33	190-200
High Temperature Epoxy	Kevlar	47	30

UMC, a trademark of Armco Composites, is a variant of SMC in which a combination of chopped and continuous fibers is deposited. Rapid curing graphite-glass hybrid polyester composites have been successfully made by this technique (21).

Thermoplastic Compounding: Thermoplastics are precompounded with chopped strand or continuous roving in screw extrusion equipment. The melt blends of well dispersed fiber and resin of controlled fiber content (10-40% by weight) are produced which are suitable as feed stock to injection molding machines. In the manufacture, fiber and resin are fed to a heated extruder, and in the extruder the resin melts and glass fibers are dispersed in the molten mass under the kneading action of the screw. Rodlike strands of mixed compound are extruded through a heated die at the end of the machine, water cooled, and chopped to length. The extrusion process can also be used to prepare unidirectional long fiber blends to make the thermoplastic equivalent of unidirectional thermoset prepregs.

2.3.2.3 Fabrication of Advanced Composites

Introduction: Many of the processing techniques used in the manufacture of fiberglass reinforced plastic parts can also be used to make advanced composites. The subject is extensively documented in the literature (22-24) and will be discussed only briefly in this report.

Some of the more common reinforced plastics fabrication processes available are listed in Table 2-17. The particular choice of process that will be most appropriate depends on the following factors:

- Part sizes, shapes, and complexities
- Properties, performance, and appearance requirements
- Composite material (resin, reinforcement, additive)
- Production volume and rates

TABLE 2-17

Reinforced Plastics Processing Methods

Bag Molding

Calendering

Compression Molding

Cold Forming

Elastomeric Tooling

Extrusion

Filament Winding

Injection Molding

Laminating, High Pressure

Matched Die Molding

Pultrusion

Reaction Injection Molding

Thermal Stamping

Thermoforming

Transfer Molding

Wet Lay Up or Contact Molding

• Required process economics (material, labor, equipment costs)

Low Volume Production Methods: Current manufacturing processes used to fabricate advanced composites parts are suitable only to reasonably low volume production. Traditional fabrication of advanced composites in the aerospace industry has entailed the cutting and manual layup of prepreg sheets in a prearranged design, and then curing the composite by the application of heat and pressure. Lay-up is a very labor intensive operation. As advanced composites parts become larger and more common, more efficient means of prepreg shaping, lay-up, and assembly are being devised. Wider tapes and broad goods dispensed from numerically controlled heads are being more extensively used. Automatic cutting techniques based on either lasers, water jets, or the Gerber reciprocating knife used in the cutting of suits, have been developed. Improved materials handling techniques are being incorporated to transfer composite plies from the cutting table to the assembly area. As examples, a vacuum assisted transfer table was developed at Grumman Aerospace Corp. in Bethpage, N.Y. to transfer 27 foot long plies needed for the B-1 horizontal stabilizer. Northrup Corp. has invested in a Cincinnati Millicron Industrial robot to perform similar operations.

Curing of the laid up prepregs is usually accomplished by a modification of bag molding. The part to be consolidated is placed in a flexible airtight sheet. A vacuum is applied to the material in the bag, and the pressure developed on the bag eliminates air, voids, and excess resin in the composite. This results in a more uniform and stronger product. A variation is also to apply external pressure to the part in order to obtain greater consolidation. This is usually done in an autoclave. A typical autoclave is a large cylindrical pressure vessel which can be heated rapidly to 350^{o}F (180^{o}C) and which can support pressures of 100 psi (690 KPa). Typical cure cycles may entail from 2 hours to 4 hours in the autoclave, followed by up to a day in a post-cure oven.

Other techniques that currently are used for fabricating complex parts with thermoset prepregs are matched die compression molding (for smaller parts) and elastomeric tooling. In compression molding, the precut prepreg is placed in a metal mold. A mating mold is placed on top. The mold assembly is then compressed between the heated platens of a hydraulic press. The prepreg conforms to the shape of the mold and cures. The cycle time is a function of the resin, catalyst, and size of the object being formed. Cycle times in molds are usually shorter than an autoclave because of better heat transfer. Depending on the system, it may be subjected to post cure in an oven. Elastomeric tooling is a variation of matched metal tooling which does not require the use of a hydraulic press. In this instance, the prepreg parts are placed in the metal molds together with a mandrel made of silicon rubber. The mold is closed, bolted shut, and placed in an oven. Thermal expansion of the rubber provides the pressure necessary to consolidate the composite.

All these fabrication methods have the disadvantage of being fairly slow and labor intensive, but have the advantage of being flexible and not requiring a major capital investment. While an autoclave is not inexpensive ($250,000), it can be used to make a wide variety of components. As a result capital costs are only a small fraction of total manufacturing costs which are dominated by labor and to a lesser extent material costs. Normalized on the basis of a unit weight of finished composite, labor content may range from 1 man-hr/lb to 10 man-hr/lb. Assuming a labor rate (with overhead) of $15/man-hour, this corresponds to from $15/lb to $150/lb of finished product. For example, Van Hamersfeld and Fogg (25) estimate that a 115 lb (52 kg) advanced composite aileron for the L-1011 airplane, would cost (for materials, fabrication and assembly) $11,100 per unit (in 1974), based on a total production run of 200 aircraft. Labor costs (for manufacturing and quality assurance) were $8500, or nearly 80% of total costs. This corresponds to a labor cost of $74/lb. This aileron however was competitive with the base line metallic part which weighed 140 lbs and cost $12,000/unit, based again on a 200

aircraft production volume. Even though the material costs were significantly higher for the advanced composite design than the metal base line design ($2600 vs. $300), total costs were lower for the composite part because of significantly lower labor costs ($8500 vs. $11,700).

2.3.2.4 High Volume Production Methods

As the production volume of composite parts increases, the fabrication techniques described above become increasingly expensive, and it becomes necessary to consider alternate manufacturing methods more suited to high volume production.

For complex shapes, high pressure molding techniques, appropriate for both thermoset and thermoplastic fiber reinforced composites, employ matched metal molds in hydraulic compression, injection, and stamping equipment. Pressures range from 200 psi for some thermosets, such as polyester, to over 15,000 psi for some thermoplastics and specialty thermosets. External heat is applied to cure thermosets and melt or soften thermoplastics. Labor costs are substantially lower and production rates substantially higher than for low pressure molding. Most processes are fully automated. Due to the cost of large molding presses and matched metal molds, high pressure molding is limited to intermediate and high volume production. Many thousands of parts have to be fabricated in order to justify the capital investment. A piece of high pressure molding equipment is usually dedicated to the manufacture of a given component.

Compression Molding: Large, automated matched die compression molding presses are currently in use in the automotive industry to fabricate component parts of fiberglass reinforced SMC, such as front end panels, truck cabs, and the body components of the Chevrolet Corvette. The metal molds have a close fitting telescoping area to seal in the plastic component and to trim the reinforcement. After the mold is closed, the part is cured typically at temperatures of from $250^{\circ}F$

($120^{o}C$) to $320^{o}F$ ($160^{o}C$) and at pressures of from 200 psi (1400 KPa) to 1500 psi (10,000 KPa) in cycles of about one to five minutes depending on the thickness, size, and shape of the object.

Thermal stamping is the plastic manufacturing process that is directly analogous to sheet metal stamping and can use the same equipment. The charge is a precut sheet, or blank, of fiber reinforced plastic, typically a thermoplastic. The blanks are preheated to just above their softening point (usually by infrared heaters) in a holding fixture next to the sheet metal stamping press. The softened sheets are then automatically fed to an open cooled matched metal die mounted in the press. The die is rapidly closed, dwells on bottom for up to 15 seconds to allow the plastic part to cool; the press is then opened and the part is removed. Total cycle time is less than 30 sec. Relatively complex isotropic parts requiring no trimming can be shaped at very high production rates in one die. If properly formulated, SMC sheets could also be used as a feed stock to this process.

Injection molding can also be used to make complex shapes. While injection molding is principally used with thermoplastics, it can also be adapted to thermosets. With thermoplastics, the molten charge of compound is forced into a cold die, where it cools rapidly to form the finished part. With thermosets, the component is heated to soften it and then injected into a hot die where curing occurs.

Injection molding can result in very economic, high volume production of complex shapes in single as well as multiple cavity molds. In terms of advanced composites technology, injection molding is limited to short fiber reinforcement. This method is currently used to make components out of carbon and carbon/glass in matrices such as nylon, thermoplastic polyester, polyphenylene sulfide, etc. (26, 27).

Reaction Injection Molding (RIM) is a relatively new plastic fabrication technology that has attracted major interest.

In this process, separate streams of highly catalyzed urethane chemicals (or epoxy precursors) are pumped to a high impingement mixing device mounted at or near the injection port of the heated matched metal mold. Chopped fiber strand is introduced to the mechanical mixing devices or following the high impingement nozzle. The viscous liquid fills the closed mold, and polymerization takes place in situ to form a strong reinforced plastic composite in less than 30 secs. For additional structural rigidity fibrous roving may be placed in the mold prior to closing. This technique has been used to manufacture large complete shapes such as automobile hoods and bumpers.

In a parallel NSF/RANN sponsored study, Hostettler observed that graphite and aramid fibers are not as readily wetted by the resin as fiberglass, and there was poor translation of fiber properties to the matrix (28). Rapid wetting is critical due to the short traction time, and further work is required, either in terms of resin modification or introduction of other high performance fibers, such as silicon carbide or alumina, that would tend to wet spontaneously.

Filament winding is a method of fabricating hollow shapes of rotation from fiber roving. In filament winding, continuous reinforcing filaments are drawn through a resin and wound under tension onto a rotating mandrel with the shape of the finished part. The filament winding machine places the reinforcement over the length of the mandrel in a predetermined pattern to achieve the desired tensile and torsional strength required for the particular application. After sufficient thickness had been built up, the laminate on the mandrel is cured at room temperature or in an oven, and is then stripped from the mandrel. Filament winding equipment enabling near continuous production is available and the process is easily automated. Filament winding was originally developed for the fabrication of high strength fiberglass pressure vessels, missile applications and piping, and even railroad cars (29, 30). It can not be used with very brittle high performance filaments such as boron, silicon carbide, and very high modulus carbon. However, more

ductile fibers such as aramid and high strength graphite may be filament wound. The escape slide/rafts inflation cylinders on the Boeing 747 are made from a filament wound Kevlar-epoxy composite, for example. Filament winding has also been used to make numerous graphite-epoxy, graphite-glass epoxy, and layered aluminum-graphite-epoxy composite automotive drive shafts.

Pultrusion is a method of producing continuous fiber reinforced composites of constant cross section. In pultrusion, continuous reinforcements are drawn through a resin bath for impregnation and then pulled through a heated hardened steel die. The die orients the reinforcement, sets the final shape of the laminate, and controls its resin content. Cure may be completed within the die or may require additional heating by infra red lamps after the composite leaves the die. Many structural shapes such as I beams, channels, wide flange beams, solid rods and bars, rectangular beams and flat sheets can be pultruded.

2.3.2.5 High Volume Manufacturing Cost Example

The cost structure of high volume operations is sensitive to raw material costs and equipment utilization rate. For purposes of illustration, hypothetical costs are presented in Table 2-18 for the manufacture of a 40 lb FRP truck hood made by compression molding of SMC, in a hydraulic press, at two manufacturing rates (12 units/hr and 60 units/hr). The SMC is assumed to contain 20% continuous glass fiber, 40% chopped glass fiber and 40% polyester resin. Based on the prices of \$0.50/lb for glass fiber and of \$0.40/lb for polyester resin, and a compounding charge of \$0.20/lb., the cost of sheet stock is \$0.66/lb. A scrappage rate of 5% is assumed, so that the effective cost of materials is \$0.69/lb.

The hoods will be made on a 3500 ton hydraulic press with a 6 ft. by 8 ft. platten which would currently cost about \$500,000, installed. Capital charges for the press will be based on 5

year depreciation, 10% annual interest and 6% maintenance charges. Mold costs, assumed to be $60,000, are amortized over a 2 year period. The equipment is operated on a two shift basis (4000 hrs/yr) and requires two operators per shift. Energy consumption is assumed to be 10 kWh per stroke for motive power, and 150 kWh for heating the molds. Electricity costs are 4¢/kWh.

As shown in Table 2-18, while product costs are principally sensitive to material costs, manufacturing rate is also important. Operating at 60 units/hour is 17% less costly than operating the same equipment at 12 units/hr.

This hypothetical exercise was extended to the substitution of a graphite-glass-polyester hybrid for the SMC compound previously assumed. It was assumed that the hybrid would contain 20% graphite continuous filaments, 40% chopped glass and 40% polyester resin. Assuming the availability of graphite at $10/lb and making the same assumptions as before, the cost of the hybrid SMC is $2.79/lb. Because of the higher stiffness of the graphite the hybrid hood will be thinner than the FRP hood and will only weigh half as much (20 lbs). Derived manufacturing costs for a hybrid hood at a manufacturing rate of 60 units/hour are also presented in Table 2-18. The hybrid hoods are twice as costly as the glass hoods at the same production rate. As will be further discussed in a subsequent section, in a real world situation, these hybrid hoods would not be manufactured unless the weight saved resulted in significant synergistic system cost reductions or in added product value that could justify this cost differential.

2.3.2.6 System Integration - Joining Methods

Composites, like other structural materials, must be joined and machined to create useful assemblies. The manner in which these operations are performed is a determining factor in the efficiency of the structure produced. Because of the directional characteristics

TABLE 2-18

High Volume Composites
Manufacturing Costs Example

Raw Material	Glass SMC	Glass SMC	Graphite/Glass Hybrid SMC
Manufacturing Rate, units/hr	12	60	60
Capital Investment $	500,000	500,000	500,000
Tooling $	60,000	60,000	60,000
Hourly Operating Costs, $/hour			
Capital Related Charges			
Interest	12.50	12.50	12.50
Maintenance	7.50	7.50	7.50
Depreciation	25.00	25.00	25.00
Amortization of Tooling	7.50	7.50	7.50
Subtotal	52.50	52.50	52.50
Labor			
2 operators @ $15/hr	30.00	30.00	30.00
Electricity			
Heating 150 kWh @ 4¢/ kWh	6.00	6.00	6.00
Motive Power 10 kW /stroke	4.80	24.00	24.00
Materials			
40 lbs/unit @ $0.69/lb = $27.60/unit	331.20	1656.00	
20 lbs/unit @ $2.79/lb = $55.80/unit			3345.00
Total Hourly Costs	424.50	1768.50	3460.00
Unit Cost	$ 35.38	29.48	57.68
Cost/Unit Weight Product $/lb	0.88	0.74	2.88

of the mechanical properties of composites and of their brittle nature, careful joint design is required to prevent stress concentrations around joints and premature failure of the assembly (31). Within these constraints, composites can be joined to each other or to other materials by a variety of common techniques.

Composites can be mechanically fastened in a manner similar to metals by drilling and joining with rivets, bolts, or pins. On the other hand, machining can be eliminated by designing holes and placing inserts in the composite fabrication operation (i.e. molding). The design of composite joints is, however, much more conservative than the design of similar metallic joints. In the aerospace industry, metallic designs are usually based on a factor of safety of 1.5 of the design allowable stress. In comparison, factors of safety for composite structures range from 2 to 3 depending on how weight critical the composite structure is.

Thermoset resin composites cannot be joined by the equivalent of welding or brazing. These techniques can be applied however to thermoplastic resin composites.

The remaining joining technique is adhesive bonding. There in an increasing tendency for composite structure to be joined to each other and to metals by adhesive bonding. The quality and reliability of adhesives have continually improved in terms of mechanical properties and allowable range of use temperatures. The main advantage of bonded versus mechanical fastened joints is that bonded joints exhibit lower stress concentrations than mechanically fastened joints and thus provide improved static strength. A major disadvantage of adhesive joining of composite structures is that a cured bonded joint is permanent and thus can not be considered for parts that need to be removed or disassembled. Thermal stresses due to dissimilar coefficients of thermal expansion of the adherents and the adhesive can markedly limit the utility of bonded joints, especially since many structural adhesives are cured

at elevated temperatures.

These drawbacks are often more than offset because the total part count, and thus the total number of joints needed, may be significantly smaller in a composite structure than in a functionally equivalent metal structure.

2.3.3 Carbon Matrix Composites

Carbon matric composites are a specialized class of composites made by pyrolysis of graphite reinforced thermoset resin matrix composites. These carbon/carbon composites can be considered to be a structural form of graphite. They possess the desirable refractory properties of graphite plus higher strength,stiffness, toughness, and resistance to thermally-induced stresses. Carbon/carbon composites are mainly used in specialized applications where bulk polycrystalline graphite cannot meet the performance requirements. Most carbon-carbon applications have come about from needs of the aerospace industry for materials of unique thermal stability, such as rocket engines and ablative reentry systems. The use of carbon/carbon composites in aircraft brakes represents the most significant commercial application of this material.

2.3.4 Metal Matrix Composites

2.3.4.1 Introduction

Metal matrix composites, as the name implies, are a class of composites in which the matrix is a metal. Interests in metal matrix composites developed as a result of the desire of the Department of Defense to obtain efficient (high specific strength and specific modulus) materials for high temperature applications where the utility of organic matrix composites is limited. In view of the inherently higher strength of metals than that of the resins used as organic matrices, metal matrix composites would have superior shear and transverse properties. Metal matrix composites would also be good thermal and electrical

conductors, be efficient sound and vibration absorbers, and have better tolerance for shocks and ballistic impacts. In some applications metal matric composites would also be expected to have better environmental resistance than resin matrix composites.

Metal matrix composites have been the subject of investigation for over a decade, as discussed in a number of recent reviews of the state-of-the-art (32, 33). The progress of the technology has been much slower than that of resin matrix technology. At the present time most of the metal matrix composite activities are all of an experimental nature. There are a number of reasons for this slow progress:

a) Metal matrix composite technology has not received the same support as resin matric composite technology.

b) Translation of fiber properties to a metal matrix composite has not always been successful. The specific interaction between the fibers and the metal matrix, either in the solid or liquid state is critical. There can be reactions between the fiber and the metal which result in the formation of interfacial compounds which can act as stress concentrators and result in a weakened composite. Conversely the metal may not wet the fibers so that poor bonding of the fiber and the matrix results. Since metal matrix systems have to be fabricated at elevated temperatures, the mismatch in coefficients of thermal expansion of the reinforcing fiber and metal matrix may result in significant internal stresses, which if not properly released, would weaken the composite.

c) Non-standard fabrication methods are required to make metal matrix composites because of problems associated with the interaction (or lack thereof) of the fiber and the matrix. A major reason for the rapid development of advanced organic matrix composites was the existence of an established fiber glass fabrication technology that was applicable to the new generation of composites. This is not the case for metal matrix composites. This technology has required the development of specialized fabrication techniques concurrently with materials development efforts.

d) Metal matrix composites are expensive specialty materials that

currently cost from many hundreds to a few thousand dollars a pound. At the moment, it is economically difficult to justify using metal matrix composites instead of metals, except for experimental or exotic purposes. There has been a chicken/egg situation in that markets and applications for metal matrix composites would not develop unless the costs of these materials decreased significantly; at the same time, without definition of sizeable markets for these materials, there has been hesitancy to invest major amounts of money in manufacturing development programs and automated fabrication equipment that could result in lower costs. The situation is changing in view of the new emphasis being placed on fabrication technology by DOD, in order to support the development of items of military hardware that have been identified as benefiting from the use of metal matrix components (34).

2.3.4.2 Matrix Metals

Metal matrix composites have been produced in a wide variety of models, ranging from low melting alloys of metals such as lead and tin, to superalloys which can operate at elevated temperatures. The majority of metal composite work has been concerned with the low density light metal alloys, aluminum and magnesium, with major emphasis being placed on using high performance reinforcement as a means of increasing the service temperature of these metals to at least 600°F (315°C). Some effort has been devoted to reinforcing superalloys in order to obtain metal structures that could operate at temperatures above 1800°F (1000°C). This work has been frought with technical difficulties because there are few materials that are truly inert at this extreme temperature. Some effort has also been devoted to improving the structural properties of denser specialty metals, such as lead and copper, with fibrous reinforcements. The goal in this case was not to develop a superior structural material, but to improve the inherently poor structural characteristics of these metals sufficiently so that they could be used without any external support in a wider variety of applications.

2.3.4.3 Fabrication of Metal Matrix Composites

Specific fabrication techniques depend on the fiber and metal being considered in the composite. Some examples are summarized below.

<u>Boron-Aluminum Composites</u>: Since boron filaments react with molten aluminum, boron-aluminum composite are manufactured by first preparing a sandwich or "preform" consisting of a mono-layer of collimated boron fibers between two thin aluminum foils and subsequentially diffusion bonding the sandwiches. This diffusion bonding operation is carried out by hot pressing at high temperatures ($\sim 965^{\circ}F$, $520^{\circ}C$) and high pressure (5000 psi, 34.5 KPa) for a period of about 30 min. Two firms in Chatsworth, CA, DWA Composite Specialties, Inc., and Amercom Inc., are the current major fabricators of boron-aluminum. Preform sheet material in sheet sizes up to 3 ft (1m) x 10 ft (3m) are available. Current price for boron-aluminum preform is about $250/lb to $300/lb. Current consumption is estimated to be about 1000 lbs/year (35).

A boron-aluminum composite is made by laying up plies of precut preform and aluminum alloy foils, such as Al-6061 or Al-2024, vacuum encapsulating the assembly, then placing it in a hot press for further consolidation. Based on the differences in the price of preform and boron filament, it is estimated that consolidation costs are approximately $100/lb, so that the total materials and fabrication costs for a boron/aluminum composite are approximately $350/lb to $400/lb.

<u>Graphite-Aluminum Composites</u>: Current graphite-aluminum composite technology is based on a manufacturing process originally developed at the Aerospace Corporation about seven years ago (36). In this process, a superficial coating of boron and titanium is applied to the fiber by chemical vapor deposition. The coated fiber is then drawn through a molten bath of aluminum (A201 alloy). As a result of the titanium-boron coating, spontaneous infiltration of the fiber occurs.

Composites can then be fabricated by the consolidation of numerous fibers, principally by diffusion bonding.

The deposition of the boron-titanium coating is the critical step in the process. Graphite fiber(s) is(are) drawn through a reaction chamber at 750^{o}C into which zinc vapor (and argon), titanium tetrachloride ($TiCi_4$) and boron tetrachloride ($B\ Cl_3$) are introduced. Zinc is presumed to reduce the chlorides to B and Ti, forming zinc chloride vapor which is removed.

Fiber Materials, Inc. (FMI) of Biddeford, Maine is the exclusive licensee for this process. The process is currently being scaled up by Materials Concepts, Inc. of Columbus, Ohio, a subsidiary of FMI. This firm is operating a pilot plant with a nominal capacity of 3000 lbs/yr. Actual production rates depend on the specific composites being fabricated.

A sodium process, also developed by Aerospace Corp., is an alternate to the CVD technology described above. In the sodium process, infiltration by aluminum is accomplished by sequentially immersing the graphite fibers in a molten sodium bath at 450^{o}C, and then in a tin-2% magnesium bath maintained at 600^{o}C, prior to immersing the fibers in a molten aluminum bath (37). Removal of trace residues of sodium is a continuing problem. This process is also used to make other metal matrix composites such as lead and copper (38).

Graphite-aluminum fabrication composite technology is being investigated by a number of firms, under contract to a number of military laboratories such as the Army Materials and Mechanics Research Center, Watertown, MA and the Naval Surface Weapons Center, Silver Spring, MD. This work includes the fabrication of bars of uniform cross section by Fibers Materials Inc.; and the manufacture of a variety of graphite aluminum composite shapes by D.W.A. Composite Specialties, Inc., using diffusion bonding technology.

Current consumption of graphite-aluminum composites is estimated to be between 500 lbs (220 Kg) to 1000 lbs (440 Kg) per year. The price for a graphite-aluminum composite shape will vary significantly depending on the specifics of the fiber and matrix, the size and complexity of the desired object. A relatively simple shaped object made out of Thornel T50 graphite - A 201 aluminum alloy would currently cost about $700 to $900 per pound, based on an infiltrated graphite filament price of $300/lb to $400/lb (35).

Alumina FP Magnesium Composites: An interesting property of alumina FP is that magnesium and its alloys effectively wet this fiber to permit spontaneous infiltration and the formation of a strong fiber/matrix bond. Alumina FP/magnesium composites with a fiber volume loading of up to 75% have been prepared by a molten metal infiltration process (40). In this process, a handleable alumina fiber FP tape is prepared using a fugitive binder. The tapes are laid up in the desired orientation to form a preform which is then put into a metal mold. The fugitive resin binder is then burned away, and molten metal is added to the mold. After allowing the metal to solidify and cool, the composite is removed from the mold. This procedure is simpler than the techniques currently used to fabricate boron/aluminum and graphite/aluminum composites, and could result in lower fabrication cover. With this process, there is the potential for reducing metal matrix fabrication costs, on a unit volume level, comparable to the fabrication costs for resin matrix composites. Because of the need to prepare a pre-form, these costs will always be higher than for simple casting.

This method is not directly applicable if aluminum or its commercial alloys are used since these materials do not wet the aluminum oxide fibers. Wetting has been obtained with aluminum-lithium alloys that contain 2% to 4% lithium, and these alloys can be used with the infiltration process described above. An alternate process has been developed at the University of Illinois by Mehrabian et al. (41), which eliminates the need for lithium as a wetting agent, and makes it possible

to produce aluminum oxide - aluminum composites with commercial aluminum alloys (such as 2024). The process is designed to produce discontinuous fiber composites that can be processed by standard fabrication techniques (such as rolling drawing, etc.) Further process details have been withheld pending filing of patent applications.

Silicon Carbide-Aluminum Composites: Continuous silicon carbide-aluminum composites that exhibit very good translation of fiber properties to the composite have been prepared under the conditions currently used to make boron-aluminum composites by diffusion bonding.

Avco Corp. is currently investigating potentially less expensive fabrication techniques that capitalize on silicon carbide's higher temperature stability characteristics. This work includes diffusion bonding of SiC-Al composites at higher temperatures nearer the melting point of the aluminum alloy so as to be able to reduce the required pressure by an order of magnitude (42).

It has been observed that silicon carbide currently made by Avco fibers are not readily wetted by molten aluminum because of the presence of a carbon rich outer layer. In order to overcome this problem, it is necessary to mask or remove this external layer. This can be accomplished by depositing a layer of titanium carbide or titanium nitride by chemical vapor deposition, in a manner similar to that currently used to render graphite filament wettable. This process modification is under current investigation. Availability of titanium carbide coated SiC filament would be used to make SiC/aluminum matrix composites by a liquid infiltration technique much in the manner of Al_2O_3/magnesium composites discussed in the previous section or by "hot molding." In hot molding, a preform is placed in a mold that is evacuated and then treated to a temperature above the solidus of the matrix alloy. Due to the deformability of the alloy and these conditions, fully consolidated composites could be fabricated without requiring the large presses currently required in diffusion bonding operations (42).

Naval Surface Weapons Center is developing discontinuous matrix composites consisting of SiC whisker reinforced (see Section 2.2.5.8) aluminum alloy. The goal of the program is to obtain a material that can be processed by conventional metal working techniques and would have the mechanical properties of steel, especially at higher temperatures, while retaining the other attributes of aluminum. Adding 25 volume percent of silicon carbide powder with a 10% whisker content, to aluminum alloy 2024, results in a composite that is 50% stiffer than the alloy, but with the same, or slightly lower, tensile strength. It is expected that as the concentration of whiskers is increased, a marked increase in both modulus and tensile strength will be achieved. Current program goals are to provide a panel form of silicon carbide reinforced aluminum with an inplane elastic modulus of $E=20\times10^6$ psi (138 GPa) and an ultimate tensile strength of 100 Ksi (690MPa), at a 15 volume percent silicon carbide loading (43).

2.4 APPLICATIONS OF ADVANCED COMPOSITES

2.4.1 Introduction

In this section, current and proposed applications of advanced composites will be reviewed. It is useful to distinguish between applications of primary interest to government agencies, mainly the Department of Defense and NASA, for military and space exploration purposes, and applications of commercial interest, such as transportation and sporting goods. It is also necessary to distinguish between wishful thinking, conceptual proposals, applications currently being studied on an experimental basis, components being tested in advanced development programs, and the relatively few instances where advanced composites have been successfully integrated into a production system.

As with any product or material, advanced composites have been used or considered for use only in those applications where it appears economically desirable to do so. Advanced composite systems have been

readily adopted in systems where their use has proven to be "cost competitive," that is the total costs of manufacturing a given system are less if advanced composites are used instead of other materials of construction. These are applications wherein opting for the use of advanced composite materials instead of an alternate material lowers design, tooling, and labor costs by a sufficient margin to more than offset any differences in materials and other costs.

Advanced composites are also considered for use in applications where they appear to be "cost effective." In these applications, the manufacturing costs of the product or system are higher than those of alternate materials, but the use of composites results in a more valuable system for which a market exists. The additional value could take the form of meeting improved performance characteristics or of lowering system operating costs (fuel, maintenance, etc.). The imperative for using advanced composites is not as high in "cost effective" applications as they are in "cost competitive" applications.

The major attributes of advanced composite systems which have resulted in their being used or considered for use in the wide range of applications discussed in subsequent parts of this section are:

1. Optimum mechanical performance characteristics per unit structural weight, resulting in either:
    a) minimum weight systems for a given performance level

    or

    b) maximum performance systems for a given weight level.

2. High stiffness - for stiffness limited applications

3. Additional degree of freedom in design resulting in
    a) more efficient use of materials,
    b) more functional system geometry,
    c) overall reductions in manufacturing costs.

4. Other unique material characteristics of particular composites that result in their being used for specialized applications, such as:
   a) corrosion resistance
   b) thermal stability
   c) abrasiveness
   d) electrical properties

A major driving force behind the substitution of advanced composite materials for metals in structural systems is that an advanced composite structure will weigh significantly less than a functionally equivalent metal structure. This is of major importance in any dynamic system.

The energy requirements, payload, and operating costs of any piece of transportation equipment are a function of the structural weight of the equipment, be it a bicycle, automobile, truck, airplane, ship, or spaceship. Reducing structural weight can result in increased payload, greater range, higher performance in terms of speed and acceleration, and/or improved fuel economy depending upon system requirements. It also follows that as the acceleration required of a system increases, the importance of weight reduction becomes of greater significance in terms of the size, fuel requirement, performance, and costs of the power plant.

A minimum weight may also be of importance if the piece is to be transported by unusual means. This has implications for systems that are to be used in remote locations accessible only by aircraft or spaceship.

This principle also applies to wide classes of equipment that use muscle power as the motive force. Better control and ease of handling, and thus improved performance, have been the driving factors behind the use of advanced composites in sports equipment or medical prostheses.

There are wide classes of high speed reciprocating, oscillating or rotating machinery where machine speed, and thus productivity, are limited by the inertia and fatigue resistance of critical moving parts. The productivity of some machine systems may be improved significantly by the selected use of composites for critical parts.

Substitution of an advanced composite for a metal in a structural component can result in weight reduction for the structure that is significantly larger than the difference in the weight of the metal component and the advanced component. Since the composite component is now lighter, any structures needed to support it do not have to be as massive, and in turn other structural elements that are a function of the weight of the total system may be made lighter. Depending on the specifics of the system, reducing the weight of a component by one pound may reduce system weight by two to three pounds if extensive weight propagation occurs. In all the above applications, some premium is associated with weight savings which impacts on the economic decision of whether or not to use an advanced composite.

In these applications the extent to which advanced composites are used in a given system is as much a function of the value associated with the weight saved as with the relative costs of using advanced composites or metals in the system. The value of weight savings depends on the application. It is much easier to justify use of advanced composites in applications that place a high premium for weight savings than in those applications where the premium is negligible. Some published values of weight premium for different applications are given in Table 2-19.

This concept of premium and weight savings can be generalized in terms of a simple mathematical relationship, as follows: Assume that a system component (or system for that matter) made out of metal has a given weight W_1 (lbs) and a given cost, C_1 (\$). Assume that the equivalent system component made out of advanced composites weighs W_2 (lbs) and costs C_2 (\$), and that furthermore, there is a cost premium C_w associated

TABLE 2-19

Value of Weight Premium for Different Applications

Application	Premium Value of Weight Saving $/lb	Reference
Space Structures	1000-1500	44
Space Vehicles	1000	45
Space Propulsion	375	44
Hypersonic Vehicles	250	44
Supersonic Vehicles	200	44
Subsonic Aircraft	125	44
Aircraft	50-200	45
	50-100	46
Trucks, Bulk Liquid Materials	2	46
Bridge, Simple	0.06	45

with weight reduction. It is logical to argue that advanced composites can be justifiably used as long as

$$C_2 - C_1 < C_w \tag{1}$$

In terms of costs per unit weight, if we define $c_1 = \frac{C_1}{W_1}$, $c_2 = \frac{C_2}{W_2}$ and $c_w = \frac{C_W}{W_1 - W_2}$, the above equation can be rewritten as follows:

$$c_2 \, W_2 - c_1 \, W_1 < (W_1 - W_2) \, c_w \tag{2}$$

By transposing terms, one obtains

$$W_2(c_2 + c_w) < W_1 \, (c_w + c_1) \tag{3}$$

or

$$\frac{W_2}{W_1} < \frac{c_w + c_1}{c_w + c_2} \tag{4}$$

or

$$\frac{W_2}{W_1} < \frac{\frac{c_w}{c_2} + \frac{c_1}{c_2}}{\frac{c_w}{c_2} + 1} \tag{5}$$

The maximum substitution that is economically feasible, on a weight percentage basis, is a function of the ratio, $\frac{c_1}{c_2}$, the unit cost of the metal to the unit cost of the composite, and of the ratio, $\frac{c_w}{c_2}$, the premium associated with a unit weight reduction to the unit cost of the composite. This relationship is expressed graphically in Figure 2-8 in which maximum values of W_2/W_1 are plotted as a function of c_1/c_2, for different values of c_w/c_2 or β for ease of notation.

Some interesting conclusions can be drawn from this figure. If there is no premium associated with weight reduction (c_w=o or β=o), the maximum amount of more expensive material that can be substituted is solely function of the relative unit costs; i.e. if the unit cost of a composite is four times that of a metal, then use of the composite can

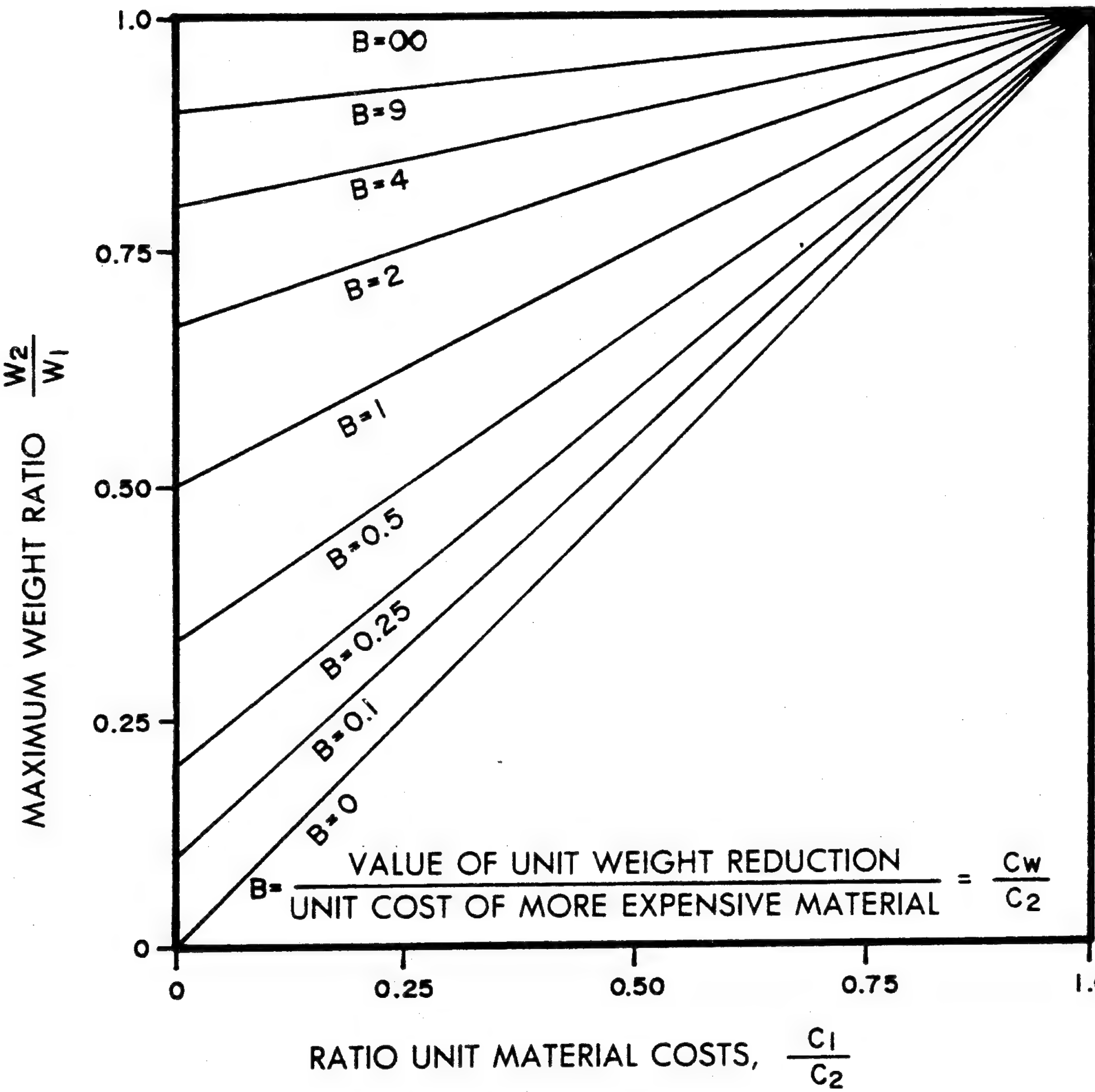


FIGURE 2-8 MATERIALS WEIGHT SUBSTITUTION AS A FUNCTION OF COSTS

only be justified if it results in at least a four-fold weight reduction. At the other extreme, if an infinite value is placed on a unit weight reduction ($\beta=\infty$), total replacement of the metal by the advanced composite is justified, irrespective of the relative cost of the materials. If $\beta=1$ and ${}^{c}1/{}_{c_2} = 0.30$, as an intermediate example, according to Figure 2-8, one could use a composite part as long as it weighed less than 75% of the metallic equivalent.

The impact of the value of weight reduction for the introduction of composite materials is illustrated by examples for which the values of weight reduction are very different as follows: In a satellite, a premium of approximately \$1000/lb can be placed on weight reduction because of reduced launch costs (45). Assume that the system component under consideration costs \$250/lb if composites are used and \$50/lb if aluminum is used. These values correspond to values of $\beta=4$ and ${}^{c}1/{}_{c_2}=0.2$. According to Figure 2-8, with these parameters, ${}^{W}2/{}_{W_1}$ has to be less than 0.84. A composite structure that is more than 16% lighter than the equivalent metal structure is cost effective even though the materials costs are five times higher. Since weight savings of well in excess of 16% can be achieved by substitution of composite for metals in many space structures, it follows that advanced composites are widely used in this type of application.

As another example, consider the replacement of a simple steel beam by a graphite epoxy composite beam of equal modulus but low density in a structure where weight savings has no value (c_w=o). The purchased cost of structural steel shapes is currently \$15.45/cwt (47) or about 15¢/lb. Installed costs for open web joists in small spans (30 ft. to 150 ft. long) are approximately \$500/ton to \$700/ton (48), or 25¢ to 35¢/lb. Assuming a standard 12 inch steel I beam (such as a 12 I 35), which weighs 35 lbs per running foot, the installed cost of structural steel is approximately \$5/foot for materials and \$3/foot to \$6/foot for labor.

Replacing the steel beam with a graphite composite beam will result in a weight reduction factor equal to the ratio of the density of the composite to that of steel, or of 0.20. Using this value in Figure 2-8, with c_w=o, the maximum permissible value of c_2, the installed price of the composite beam, will be \$1.95/lb based on a value of c_1 = 0.30 ¢/lb. Depending on whether it is assumed that erection costs are function of the number of beams installed or of their weight, based on a 15¢/lb labor cost for a steel beam, installation costs for an advanced composite beam graphite can range from 15¢/lb to 75¢/lb. The maximum purchased cost of these beams would have to be of the order of \$0.70/lb to \$1.30/lb or approximately \$1/lb.

The most optimistic projections for the cost of high performance filaments are of the order of \$5/lb for pitch graphite in large volume. The material costs for a composite beam that contains 60% filament and 40% resin (at \$0.50/lb) would be \$3.20/lb. With fabrication and distribution costs and profit it is doubtful that the composite structures could be sold for less than \$5.00/lb; and thus would be too expensive, within the foreseeable future, to be considered for simple structural applications where weight savings has no value.

It is furthermore doubtful that even a graphite-glass hybrid I-beam structure could become cost competitive in this sort of application. Consider a graphite/glass resin composite I beam which would contain graphite in the outside faces of the flange section and glass in the inside faces of the flange and in the web. Assuming that the beam contains 20% graphite, 40% fiber glass and 40% resin, the density of this beam would be 20% higher than of the graphite-resin composite, and the modulus would be about 25% lower. To maintain the constant stiffness factor, the hybrid will have to be larger than either the graphite-resin or steel beam. Based on the above, assuming dimensions of standard I beams, a graphite-glass hybrid beam would be approximately 30% larger in volume, and thus weigh about 80% more than an all graphite beam. With reference to a steel beam, the weight reduction factor would

be 0.36, which implies that the installed cost of the hybrid beam would have to be less than \$0.83/lb. With installation costs of the hybrid beam estimated to range from 15¢/lb to 40¢/lb, it is calculated that the composite beam would have to sell for about 43¢/lb to 68¢/lb, or about 55¢/lb. With graphite at \$5.00/lb and fiber glass and resin at \$0.50/lb, raw materials costs would be \$1.30/lb. Assuming the same fabrication and distribution costs as for a graphite composite, it is doubtful that this hybrid beam could be sold for less than \$3.00/lb, and it, too, would be too expensive for the intended application.

For the above reasons it is doubtful that advanced composites would be used in applications such as the structural support of a skyscraper or the stiffening truss of a suspension bridge. In both these cases, the structural requirements are governed by forces, particularly wind loading, that are much larger than, and independent of, the weight of the structure. Replacing the steel elements of a skyscraper with elements of advanced composite materials would result in a structure of lower weight but would not significantly change the forces the structures would have to carry. As a result, there would be no advantage for using advanced composites in these structures.

2.4.2 Military and Space Applications

2.4.2.1 Military Aircraft Structures

Three branches of the U.S. military service have supported the development and use of advanced composites in military aircraft since the early sixties. Reviews of the development in the fields have been published by Salkind (49), and Harris (50). Since 1960, these programs have progressed through the various phases of materials development, design concepts, manufacturing prototype evaluation, component production and service experience. Use of advanced composites has advanced from replacement of metal in a few selected secondary structures to current designs in which advanced composites represent 20% of the structural

weight, including primary structures critical to the air-worthiness of the plane. Projected usage of composites is expected to increase to 30-65% of the total structural weight for high performance fighter aircraft by 1990, concurrently with a 20% reduction in costs.

The major components for which limited production experience has been obtained prior to 1975 are given in Table 2-20. Other more recent Air Force fabrication programs include the YF-17 fuselage, the B-1 horizontal stabilizer, F-15 speed brakes, F-16 horizontal stabilizer, and ADP (Advanced Development Program) torque box. Air Force advanced composites service experience as of 1975 is summarized in Table 2-21. The first production advanced composite to reach flight status was the Grumman/U.S. Navy F-14 horizontal stabilizer which has been in service since 1970. The structure consists of boron epoxy skins adhesively bonded to a full depth aluminum honeycomb core, and bonded to a stepped metal pivot fitting. Between 1970 and 1977, 250 F-14's have been built which have required over 1000 boron-epoxy skins. Additional Navy advanced composite service experience with graphite-epoxy components is summarized in Table 2-22.

A number of important composites applications were included in the B-1 bomber program which was cancelled by Presidential veto. These included the horizontal stabilizer, vertical stabilizer, weapons bay doors (6 ea.), avionics access doors (6 ea.), dorsal longeron the No. 3 left side slat, and the No. 3 left side flap (51, 52). The total weight of these components, 5581 lbs (2536 Kg) was 1899 lbs (863 Kg) less than the all metal baseline system. The life cycle costs for the composite components ranged from 0.5% less to 47.5% less than the metal equivalents. The 26 ft. (7.8m) long horizontal stabilizer alone would have required 1840 lbs (840 kg) of advanced composites (53).

Advanced composites applications in U.S. military aircraft that are currently in production are summarized in Table 2-23. As mentioned above, the F-14 is the oldest of these production aircraft.

TABLE 2-20

Advanced Composites Use

In Military Aircraft

Limited Production Experience

Component	Composite	Preproduction Program Duration
F-4 Rudder	B/E	1968-1969
C-5 Leading Edge Slat	B/E	1969-1970
F-14 Horizontal Stabilizer	B/E	1970-1975 (currently in production)
F-111 Wing Box Doubler	B/E	1971
F-111 Underwing Fairing	G/E	1971
F-15 Empennage	B/E	1971-1975 (currently in production)

Source: Reference 50

TABLE 2-21

Air Force Advanced Composites

Service Experience

Component	Material	No. In Service	Approx. Cum. Flight Hours (up to 1975)
F-111 Wing Tracking Edge Panel	Boron/Epoxy	21	32,050
C-5A Leading Edge Slat	Boron/Epoxy	11	23,450
F-4 Rudder	Boron/Epoxy	45	51,000
C-141 Gear Pod Door	Boron/Epoxy	1	8,800
F-111 Underwing Fairing	Graphite/Epoxy	286	44,700
F-15 Empennage	Boron/Epoxy	33	5,000

Source: Reference 50

TABLE 2-22

Evaluation of
Graphite-Composite Components
in Naval Aircraft

Component	No. of Aircraft	No. of Components	Start of Flight Evaluation
BOM 34E wing	8	8	Aug 1973
S-3 Spoiler	14	28	May 1975
F-4J Access Door	4	8	Dec 1975
F-14 Landing Gear Door	9	18	May 1976
F-14 Overwing Fairing	5	10	May 1976
Total	40	72	

Source: Reference 50

Use of composites in the USAF-McDonnell Douglas F-15 "Eagle" entered production status in 1975. To date (1/78), 200 boron/epoxy empennages and 400 graphite-epoxy speed brakes have been built. The speed brake was incorporated as a running change. Production is of the order of 100 planes/year.

The USAF-General Dynamic F-16, which went into production in 1977, consumes approximately 200 lbs (90 Kg) of graphite-epoxy per aircraft. Production of this aircraft is about 150 planes/year and may increase threefold by the early 1980's.

The U.S. Navy-McDonnell Douglas F-18 Hornet multi-mission strike fighter differs from previous aircraft design in two ways (54): 1) the airframe will consist of about 10% of graphite-epoxy composites whereas prior aircraft contained less than 2% composites,and 2) advanced composites will for the first time be used in a fighter aircraft as primary structural materials in the upper and lower wing skins. Fourteen pre-production aircraft will be made this year for testing and flight evaluation.

McDonnell Douglas is also currently developing the AV 8-B Advanced Harrier aircraft for the U.S. Navy. Under a prototype program, two aircrafts will be built which will use about 1000 lbs (450 Kg) of advanced composites each (55). This represents about 20% of the structural weight of the aircraft. Two prominent changes from prior design practice are the use of composites in the forward fuselage and the use of composites in the wing substructure. The spars and ribs, as well as the wing skins, will be made from graphite-epoxy composites. About 70% of the wing weight (15 percent of the aircraft structural weight) will be made of graphite-epoxy composite, resulting in a projected wing weight saving of 20%.

In 1978, NASA will begin flying the Rockwell built HiMAT aircraft which will employ technology that could be incorporated

TABLE 2-23

Advanced Composites Applications In

Military Aircraft

Currently in Production

Plane	Material	Component	Advanced Composites Utilization: Weight per Aircraft lbs (Kg)	Advanced Composites Utilization: Weight Percent of Aircraft Structural Weight
F-14	Boron Epoxy	Horizontal Stabilizer	186 (85)	0.8%
F-15	Boron-Epoxy	Empennage	215 (98)	1.6%
	Graphite Epoxy	Speedbrake Fins		
F-16	Graphite Epoxy	Empennage Fin Covers	180 (82)	2.5%
F-18(*)	Graphite Epoxy	Upper & lower wing skins, horizontal surfaces, speed brake panel, fuselage ventral section, leading edge extension, landing gear doors	1100 (500)	9.5%

(*) Pre-production

into fighter aircraft of the 1990's (56). Under a joint NASA/USAF contract, Rockwell is building two Highly Maneuverable Aircraft Technology remotely piloted research vehicles. The HiMAT vehicle is currently designed with about 25% of the structural weight of 3400 lbs (1545 Kg), or 850 lbs (386 Kg) in graphite-epoxy composites.

Extensive use of advanced composites will be required for the Navy's proposed Type A vertical and short takeoff and landing (VSTOL) aircraft. In this aircraft, a premium is placed on airframe weight reduction because of propulsion weight considerations. For example, in the V-530 design proposed by the Vought Corp. (Div. of LTV, Inc.) more than 50% of the airplane empty weight is graphite-epoxy composite (57).

Various other design concepts are being studied by different airframe manufacturers for the advanced fighter of 1990. On the average, advanced composite utilization would increase to about 4300 lb/airplane (1960 Kg/airplane), or 36% of the structural weight (58), and in some of the designs, composite utilization was even higher, of the order of 65% to 75% of the structural weight (59, 60). Assuming an average composite use of 4300 lbs/aircraft and a 60% fiber content, an annual production of 200 military aircraft would consume over 500,000 lbs (230 M. Tons) of high performance fibers per year.

These figures indicate that advanced composites most likely will be a mature technology, at least in terms of use in military aircraft structures, by 1990. By that time, advanced composites will be sufficiently well established that they will have become the base line material for design. This maturation process will have taken 30 years.

2.4.2.2 Helicopters (Military and Commercial)

The introduction of advanced composites in helicopter design has been slower than in the high performance aircraft described

in the previous section. With the exception of the rotor blades, there is relatively little use currently being made of advanced composites in helicopter structures. The first applications of advanced composites in Army helicopters were made on the Sikorsky/U.S. Army CH54 in 1972. These were the reinforcement of the aluminum stringers on the tail cone with unidirectional boron-epoxy strips, and a boron-epoxy tail skid. The Sikorsky-U.S. Army UH-60A Blackhawk, and the comparable U.S. Navy SH60B Lamps, the current state-of-the-art military helicopters utilize about 150 lbs (70 Kg) of aramid epoxy composites in the secondary structural elements, and only a small amount of graphite in the rotor structures.

Composites have been used extensively for helicopter rotor blades. Initially fiberglass composites replaced metal in the blade structure because composites were easier to fabricate, had better resistance and improved structural damage tolerance. Most blades are now hybrid systems, consisting of fiber glass selectively reinforced with aramid or graphite fibers, such as the Blackhawk and CH-46 main rotor blades. Hughes Aircraft has developed a unidirectional aramid-composite blade which may go into production. A unique application of composites to rotors is the Sikorsky/U.S. Army UH-60 bearingless tail rotor in which a unidirectional graphite epoxy spar extends from the tip of one blade through the hub to the tip of the other blade. This approach has resulted in a simpler, lighter, and more reliable design than would have been possible with metal. A number of experimental blades have been made with boron-epoxy and with graphite-epoxy composites (49, 61) on an experimental basis.

In addition, an Advanced Structure Technology Demonstrator (ASTD) program has been formulated to develop a base line design that makes maximum use of advanced composites and provides a test bed for structural testing and service evaluation. The ASTD aircraft is intended to overcome the limitations of replacement components and show the synergistic effect of advanced composites on the structural weight, design gross weight, and power requirements. Components that would be made from

advanced composites would include the main rotor hub end blade assembly, an all welded metal composite reinforced gear box, molded composite air frame shell structure, hybrid sandwich floor construction, tail boom assembly, etc. For lack of funds, this is still only a planned program.

The gear box would be an interesting application of metal matrix composites. Boeing-Vertol is fabricating an experimental gear box housing (12 in. or 30 cm in diameter) made of alumina reinforced magnesium composite. It is expected that there will be a significant reduction in the noise and vibration transmitted into the aircraft, which place severe limits on the endurance of the flight crews. Similar noise transmission problems exist in many industrial environments, and if this program is successful, it would have a potential utility that is much broader than helicopter design.

Advanced composites are also being considered for use in non-military helicopters, utilizing the technology developed in military systems. A few proven components are being selected for use in commercial helicopters, as represented by the advanced composite structures awaiting FAA certification listed in Table 2-24. As experience is gained with these components in commercial use, and with other components in military helicopters, more extensive use of advanced composites will be made in commercial helicopters. A design study of the Boeing Vertol BO 105 indicated an 11% weight reduction was possible if parts made of aluminum and FRP were replaced by aramid composites (62).

In 1977 U.S. helicopter manufacturers shipped approximately 950 commercial aircraft having a total value of about $400 million compared to 775 units valued at $305 million in 1976. U.S. commercial helicopter shipments in 1978 will be about 1100 units with a value in excess of $425 million. This corresponds to a 20% annual growth. If a more modest 15% annual growth is forecast, about 5000 commercial helicopters will be sold in 1990. Assuming an average use of 300 lbs of advanced composite per aircraft, and a fiber content of 60%, approximately

TABLE 2-24

Advanced Composites Helicopter Components

Awaiting FAA Certification

Company	Aircraft	Component
Bell/Textron	214	Main Rotor Blade
	106	Vertical Fin, Skids
Boeing-Vertol	CH 47 D	Main Rotor Blade
	BO 107	Main Rotor Blade
Sikorsky/U.T.C.	S 76	Blades, Stabilator, Main and Tail Rotors

Source: Reference 63

900,000 lbs/year (400 metric tons/yr) of high performance fibers would be required.

2.4.2.3 Jet Engine Components (military and commercial)

Use of advanced composites in engine structures theoretically offers a major potential for weight reduction, cost reduction, and increased engine efficiency. Components that could be made out of advanced composites include fan blades, stator blades, stator vanes, compressor blades, and frame sections. Extensive use of composites could result in weight and cost reductions of the order of 30-45% as shown in Table 2-25. While organic matrix composites can be used in the cooler regions of a turbine, extensive use of advanced composites would require metal-matrix systems. Because of their higher impact resistance and better thermal stability, boron-aluminum composite compressor blades have been used on an experimental F-100 engine (Pratt & Whitney), which was flight tested successfully for several hundred hours. Borsic-aluminum composite fan blades have been developed by Pratt & Whitney for the JT 8D, a commercial engine that powers the Boeing 727 and the McDonnell Douglas DC-9. Borsic-aluminum composite compressor blades have been developed for use in the compressor section of the TF-30, a military engine for the Grumman F-14. Pratt & Whitney has also developed a graphite epoxy composite first stage fan blade for the JT 9D, a commercial engine now in use on the DC-10; and is experimenting with the use of graphite-epoxy composite for fabrication of JT 9D fan exit cases currently made of titanium (64).

There are several major problems to be overcome before advanced composites can be used in aircraft engines. These include foreign object damage, reliability, quality control and a general lack of confidence due to limited experience. Foreign object damage (FOD) has been of continuing concern since the development of the Rolls Royce RB-211 engine. The design of this engine was based on the use of graphite-epoxy fan blades, but they proved to be insufficiently resistant to FOD.

TABLE 2-25

Potential Impact of
Advanced Composite Structures in
Military Engines

Engine	Pounds of Composite	Estimated Savings Weight (lb)	Cost (%)
TF 39	186	37	44
TF 34	68	32	31
CF 6	280	37	39
F 101	41	46	38

Source: Reference 45

The scrapping of this design led this company to bankruptcy. It also nearly resulted in the bankruptcy of the Lockheed Aircraft Corporation that was planning to use the Rolls Royce engine in its L-1011 and had supported the English firm. This experience has delayed commitment to production of an advanced composite engine until essentially total assurance is obtained that the foreign object problem has been successfully met, and until an extensive data base on the advanced composites that would be used is obtained.

There are currently extensive research and development efforts devoted to developing improved materials and manufacturing methods to achieve these goals, principally under the sponsorship of DOD and NASA, but it is not possible to forecast at present when advanced composites will find major use in production aircraft jet engines.

2.4.2.4 Missile Applications

Rocket and missiles were among the earliest applications of advanced composites, with notable use being made in critical structures, reentry vehicle thermal protection systems, and rocket components. The state of the art in this area is believed to be represented by the Trident (C-4) I.C.B.M. which used graphite composites and aramid composites to improve range and performance. The critical equipment section structure is made from graphite-epoxy composite. Graphite fiber composites are also used in port openings for nozzle and igniter assembly installation, as well as the rocket nozzles. The missile cases are made with aramid-epoxy composites and are 25% lighter than FRP cases. More extensive use of advanced composites, including graphite-aluminum composites, is planned for this system (65).

Composites will also be used extensively on the new MX missile. Applications would include motor cases (aramid-epoxy), upper stage adapter structure (graphite-epoxy, possibly graphite-aluminum) and re-entry vehicle substructure (graphite-epoxy) (66).

The metal wings currently on the Tomahawk cruise missile made by General Dynamics/Convair will be replaced by aramid-polysulfone wings. This results in a light, low cost system of low radar cross section. In future systems, alumina fibers may be added to the composite to improve compressive strength. Production of this system is expected to reach 150 to 200 units per month in the early 1980's (67).

Because of the high premium placed on weight reduction and performance in all the above systems, future advanced composite usage in this area will be limited more by the material properties rather that by first costs. As improved materials are developed they will tend to be rapidly incorporated in these systems.

2.4.2.5 Space Systems (including Commercial Satellites)

Utilization of advanced composites in space structures has increased rapidly in a short period of time. One of the first applications was a cooler cover of graphite-epoxy composite weighing less than 1 lb/(0.5 Kg) on the 1500 lb (680 Kg) Air Force Synchronized Meteorological Satellite (SMS) launched in 1974. Explorer 49 had light support booms made of boron/epoxy. Pioneer 10 had an antenna feed strut, platford strut, and magnetometer boom made of boron/epoxy that had a combined weight of about 3 lbs (1.4 Kg). In comparison, over 58% of the components on Ford Aerospace's Intelstat V, which will be launched in 1979, will be made of advanced composite materials, principally graphite-epoxy composite. These components represent 45% of the launch weight of the satellite which will be about 1400 Kg (3100 lbs) (68). This satellite will have a deployed wingspan of 50 ft. (17m). Graphite-epoxy composite is used extensively in the largest components, the 58 ft. (16 m) long deployable solar array and an 8 ft. (2.9m) diameter reflecting antenna. Graphite-epoxy composite is an excellent material for communications satellites because of its high strength, high modulus, and thermal stability. Aramid-epoxy is used where low thermal conductivity is required. Intelstat V is considered representative of the communications

satellites that will be launched in the 1980's, and wherein advanced composite materials will be the materials of choice.

The biggest single space systems use of advanced composites has been the space shuttle orbiter. The orbiter utilizes about 5000 lbs (2300 Kg) of advanced composite structure in various components. As shown in Table 2-26, use of composites in these components results in a weight saving of over 3000 lbs (1350 Kg) when compared to an all metal structure. This represents about 5% of the structural weight of the orbiter.

It is expected that in future space transportation systems more extensive use of advanced composites will be made to increase the payload of the system. If the primary structure control surfaces and tanks could have been made of higher temperature advanced composites, a 25-30% reduction in structural weight would have been obtained (45).

As part of NASA's space shuttle payload deployment and retrieval mechanism, a 50 foot manipulator arm is under development by Convair Division, General Dynamics Corp., and the National Research Council of Canada. The three piece arm structure will be made of hollow tubes of ultrahigh modulus graphite epoxy composite. The manipulator arm will be capable of deploying a 32,000 pound (15,000 kg) payload in space.

There is developing interest on the part of DARPA, the Air Force (AFML and SAMSO) and NASA in large space platforms, that potentially would have dimensions of kilometers. Progress in the scientific exploration and industrialization of space will result in increasing consumption of advanced composite materials. The issue in this case is not whether to use advanced composite materials, but which ones and how to deploy them.

Current systems are examplified by Intelsat V which is assembled and packaged in collapsed form on earth, and then

TABLE 2-26

Applications of Advanced Composites on the Space Shuttle Orbiter

Component	Material	Weight Savings, lb	(kg)
Ti Aft Thrust-Structure	Boron/Epoxy Reinforcement	900	(410)
Payload-bay Doors	Graphite/Epoxy	1,070	(486)
Purge and Vent Lines	Aramid/Epoxy	200	(90)
Mid-Fuselage Frame Tubes	Boron/Aluminum	180	(82)
Orbital Maneuvering Pods	Graphite/Epoxy	300	(136)
Pressure Vessel Overwrap	Aramid/Epoxy	435	(198)
TOTAL		3,085	(1,402)

Source: Reference 50

unfurled by spring action in space. As the characteristic dimension of the platform exceeds 100m to 300m, this method of deployment is no longer feasible and it becomes necessary to consider space assembly of structural elements fabricated on earth, much in the manner of a child's erector set. Very large platforms (kilometer size) may require fabrication and assembly of the structural elements in space.

A number of ingenious approaches to the problem have been proposed. Lockheed Missile and Space Company, Inc. has proposed that large space platforms of any size could be built with earth fabricated tubular elements that would be assembled in orbit (69). The basic element in Lockheed's system is a thin (0.30 in. or 0.76 mm wall thickness) tapered tube (tube diameter varies from 10 cm (4 in.) to 25 cm (10 in.) that is 10 meters (30 ft.) long. Each tube, which would weigh about 5 Kg (11 lbs), is made of filament wound graphite epoxy composite that is fitted with quick connecting aluminum fasteners at each end. By tapering the tubes, stacks of nestled tubes can be transported in a manner that makes efficient use of shipping space.

In orbit, the tubes are deployed and assembled automatically in a cellular array. The basic module is a tetrahedron in which each side is comprised of two tubes joined at their wide end. A space platform of any size could be built by simply adding more structural cells. A single platform a half mile (0.8 Km) square would require approximately 58,000 tubes and weigh about 660,000 lbs (280 metric tons). Interestingly, this is greater than the current total U.S. consumption of graphite-epoxy composite prepreg. According to Lockheed, there is no advantage in considering space fabrication of structural elements for large platforms because the hauling capacity of the space shuttle for low density composite materials is volume limited rather than weight limited. This company feels that the tubular element approach they have proposed makes maximum use of available shipping space. Lockheed is currently under contract to NASA Langley to develop the technology to fabricate these tubes. A vertical filament winding machine that fabricates scaled

down tubes (8 ft. (2.5m) long) has been built, and the prototype tubes are being evaluated.

A different approach to large space structures is being taken by Convair Division of General Dynamics Corp. Convair foresees the need for being able to fabricate advanced composite structural elements in orbit from raw materials shipped from Earth. According to Convair, a high temperature thermoplastic, such as polysulfone, and spools of high strength filament would be shipped from Earth (67). Tubular structural elements would be fabricated by extrusion in orbit, using focused solar energy to heat the cross head extruder. The reinforced elements could be automatically cut to size and welded, presumably by focused solar energy, as required.

Both these approaches use organic matrix composites as the basic structural material. There is some concern about the thermal conductivity and long term resistance of these materials to the environmental conditions of space, in particular degradation due to ultraviolet radiation. The advanced composites community has strong proponents who advocate the use of metal matrix composites for this class of application.

NASA plans to have an experimental 300 meter platform in space by 1983. Given the rapid advance of satellite technology and the major contributions of the technology to commercial and military communications, military surveillance, and scientific observation, this area will continue to grow in importance. If the world of Buck Rogers arrives by the end of the century, it will be made of advanced composites. Whether it will arrive is another issue.

2.4.2.6 Other Military Applications

Advanced composites are currently being considered as candidate materials for a wide range of other military applications,

some of which support specialized military requirements, while others are the military counterparts of commercial equipment. Representative examples are discussed in this section.

Mobile Army Equipment: Perhaps the most radical departure from conventional military operations in the past two decades has been the growing trend to air mobility. This has brought tactical reliance on helicopters and a consequent need for light weight reliable vehicles and the field equipment and material to be carried by them. While the Army has given highest priority to exploring the use of advanced composites in helicopter structures for cost-benefit reasons, the Army has also explored the use of composites in applications such as weapons-gun tubes, rocket launchers, missile structures and penetrators; bridging and associated craft-trusses, beams, boat hulls and engines; ground vehicles-bodies, frames, drive shafts engines and suspension systems; piping-water, sewage and POL (Petroleum Oil and Lubricants) distribution, logistic containers and protective coverings. Much of the work involving the use of advanced composites in weapons is classified.

The ability to cross rivers under battlefield conditions is an inherent part of the Army's mobility requirements. It is expected that under these conditions existing bridges would have been destroyed, so that ground forces will have to be provided with portable bridges. These bridges will have to be able to support heavy tracked equipment. Portable aluminum bridges have been developed but these exhibit poor sway and stiffness characteristics. Convair Division of General Dynamics Corporation has been under contract to MERADCOM to carry out preliminary feasibility studies for the design and fabrication of portable bridges made of advanced composites which would be lighter and stiffer than existing metal bridges.

Most of the effort related to the use of advanced composites in ground vehicles is similar in nature to the work being carried out in the commercial automotive area (see Section 2.4.3). In

addition, the military is also investigating the use of advanced composites in heavy tracked vehicles in applications such as an advanced composite loop wheel substitute for a standard tank tread that would reduce vehicle weight by 25% and provide good ballistic protection (69), and tank tread elements made of metal matrix composites (70).

Naval Ship Structure: The Navy is currently funding a number of programs to develop various advanced composite structural elements for naval ships. These include hydrofoils, hydrofoil flaps, and submarine sensor masts.

Two full scale (48 in. 122 cm) long) experimental graphite epoxy box beams representative of the main load carrying structural box of the forward foil of the Navy's experimental Patrol Craft hydrofoil (PCH-1, High Point) are being procured by the David W. Taylor Naval Ship Research and Development Center for evaluation and as possible replacements for stainless steel or titanium alloy beams. Two graphite-epoxy hydrofoil control flaps developed under contract by Boeing Marine Systems will also be evaluated by the Center. These control flaps will be approximately 7 ft. (2.1 m) long and 1.5 ft. (0.5 m) in chord. One of the flaps will be tested for fatigue and the other flap will be installed on the aft inboard foils of the PCH-1, replacing one of the steel flaps, and will be put into service for evaluation on the ship. It is anticipated that the composite flaps will provide the Navy with its initial demonstration of the use of advanced composites in a marine environment (40). Aramid composites are being used successfully in racing boats as discussed in section 2.4.3.2. The speed and endurance record of aramid boats in offshore power races has served to spark the interest in Coast Guard and military patrol boats. Several prototypes are presently in building testing stages. It is likely that these small patrol craft will be the first production use of advanced composites in military marine structures.

Electronic Applications: Advanced composite materials are being investigated for a number of electronic applications. These include graphite epoxy composites for shipboard satellite communications antenna, alumina FP Kevlar high temperature resin composites for

radar transparent aircraft structures (18) and preliminary research on alumina FP- glass matrix composites as potential materials of construction for missile seeker domes (71).

2.4.2.7 Energy Storage and Generation Equipment

Fly Wheels: A fly wheel is an energy storage device in which kinetic energy is stored in a disk rotating at high speed. The performance criterion for a fly wheel is the kinetic energy per unit mass, which is proportional to the specific strength of the material of construction of the rotating disk. Aramid-epoxy composites are the current materials of choice in this application. Based on existing technology, the energy density storage potential of an aramid fly wheel is 84 wh/lb (185 wh/kg) (72). This is nearly three times the storage capacity of current automotive lead/acid batteries.

Lawrence Livermore Laboratory of the University of California manages the fly wheel program sponsored by the Department of Energy (DOE). There is also interest in fly wheels by the military services, the U.S. Postal Service and the Electric Power Research Institute. Principal applications of interest are as energy storage devices for automotive applications and for electric utility load leveling and peak power sharing. Fly wheels are being considered for electric hybrid vehicles as a means of providing reserve energy for vehicle acceleration. A prototype U.S.P.S. electric-fiberglass fly wheel hybrid mail delivery vehicle has been built and is being evaluated. A more advanced electric fly wheel-hybrid vehicle is being built by Garrett Corp. under contract to DOE. Further development will continue under the program management of NASA/Jet Propulsion Laboratory in Pasadena, CA. Numerous technical difficulties have to be resolved before fly wheels can be considered for production vehicles. These include manufacturing and reliability, resulting vehicle handling characteristics, safety, and public acceptance.

Nuclear Submarine Batteries: Lead and lead alloys

are materials that have exceptional chemical and electrochemical properties, but poor mechanical properties that impose severe limitations on their use. Fiber reinforcement of lead appears to be a promising way of obtaining a material that retains the general physicochemical properties of lead but has the mechanical strength and modulus of steel. A significant amount of work has been done by Amateau and coworkers at Aerospace Corp. (38) on the reinforcement of lead with fiberglass, graphite fibers, or alumina FP.

There are large lead-acid electric storage batteries on board nuclear submarines as a source of auxiliary power. These batteries have to be replaced every five years because the lead plates creep under their own weight and ultimately short out. This entails a major overhaul of the ship in drydock since the batteries are accessible only by cutting a hole through the side of the ship. The Navy is interested in increasing the battery life to ten years to match the overhaul period of the nuclear reactors, and thereby eliminate the extensive costs of the intermediate drydocking operation and lost sea duty time.

Under contract to the Naval Ship Surface Weapons Center, Gould Corp. of Chicago is developing an experimental submarine battery in which the plates are reinforced with FP alumina fibers. Preliminary results have been very encouraging. Addition of 5% alumina fibers appears to significantly strengthen the lead without affecting the electrochemical properties of the battery (73). The corrosion problems experienced with graphite-lead composites in the presence of battery electrolyte have not been experienced with alumina FP reinforced lead.

Work is continuing on laboratory prototype systems. A significant amount of development and manufacturing technology effort is still required before an operational battery is obtained.

Speculating on the future, fiber reinforced lead may find applications in other batteries than heavy submarine batteries.

FP reinforced lead could potentially be used in automotive batteries or in batteries for electric vehicles. The increased strength and stiffness of the lead might allow a totally new approach to the design of a lead-acid battery plate that would be thinner than current designs and thereby significantly increase the specific energy storage capacity of the battery. If a 50% increase in specific energy storage capacity could be achieved, fiber reinforced lead acid batteries would be the equal in performance of nickel-zinc batteries currently being considered for use in electric vehicles. Because of the high cost of and low availability of nickel, fiber reinforced lead batteries could be a cost-effective energy storage system for electric vehicles.

High Density Electrical Energy Conversion Devices: Metal matrix composites are uniquely suited to application in dynamic and static components of high density energy conversion devices such as superconducting magnets and homopolar generators. Superconducting magnets are currently used in experimental MHD devices and are being contemplated as containment devices for controlled thermonuclear (fusion) reactors. The energy conversion efficiency of current fossil fuel thermal electric power plants is of the order of 35% to 40%. With MHD systems, energy conversion efficiency would be increased to 60%. Fusion reactors would not require fossil fuels. It is currently projected that a prototype MHD power plant will be in operation by 1990 and that MHD power plants could provide a significant fraction of electrical energy requirements by the end of the century. The goal of the fusion reactor program is to provide one third of the network energy requirements by the year 2050 (74).

The current carrying capacity of the present generation of superconducting materials, such as niobium-tin, is a strong function of the strain experienced by these materials. The resistivity of these materials increases rapidly at strain levels greater than 0.1%. Any electromagnet that generates an external magnetic field also experiences internal mechanical stresses that increase with the intensity of the field being generated. High field superconducting devices will

require very strong and rigid structures - strong enough to support high magnetic forces, and rigid enough to prevent deformation of the superconducting elements.

Currently superconducting wire restraint members principally use stainless steel. A light weight experimental system has been built by Magnetic Corporation of America with fiberglass epoxy reinforcement (75) and FRP materials may be satisfactory for MHD systems. If costs of advanced composites were to drop significantly, then they would become competitive in MHD applications. However the much more stringent requirements of fusion power reactors, where weight, high temperatures, and isotope inventory are major considerations, preclude the use of organic matrix materials in favor of either graphite or alumina reinforced aluminum composites (74). The Cryogenic Division of the National Bureau of Standards in Boulder, CO has an ongoing program in this area.

Homopolar-rotor current collection is a serious problem in advanced homopolar devices, which are the electrical analog of the mechanical fly wheel discussed earlier. Both the high speed and the necessity of providing electrical conductivity have required the use of exotic systems such as liquid sodium contacts. Conventional carbon-brush systems are not sufficiently conductive and wear too rapidly. Aerospace Corp. has recently proposed that graphite fiber copper matrix composites would be particularly suitable for such sliding system applications and is planning to undertake a research program to develop such contacts (76).

2.4.3 General and Commercial Applications

2.4.3.1 Sports and Recreational Equipment

The sports and recreational equipment market was the first commercial application of advanced composite materials. Advanced composite materials have been successfully used in shafts for golf clubs,

fishing rods, tennis (and other) rackets, archery equipment, hang gliders, etc. In all these applications, only a small amount, typically less than 100 gr of advanced composites, is used in an expensive final product. The principal U.S. manufacturers of advanced composite sporting goods are listed in Table 2-27.

Shafts for golf clubs were the first high volume application of graphite and, to a lesser extent, of boron for sports equipment. The high specific stiffness of these advanced composite materials results in a lighter shaft (85 gr to 95 gr for a typical graphite epoxy shaft), permitting proportionally more weight in the head of the golf club which appears to result in greater driving distance. During 1973 and 1974, more than one million shafts, approximately 3% of all golf shafts manufactured in the U.S. during that period,were made of graphite composites.

After an initial glorious entry into the market, sales of advanced composites golf shafts tapered and is currently estimated to be about 200,000 shafts/year, or about 1% of the ~20 million shafts/year purchased in the U.S. (77). One of the reasons for the diminished demand for advanced composites shafts is that the manufacturers of steel golf shafts, upon seeing their market being invaded, have redesigned their products and have developed light weight metal shafts. An example is the Ben Hogan Legend Shaft which weighs 113 grams.

Major demand has developed in the past few years for fishing poles made of advanced composite materials, principally graphite-epoxy, graphite-glass hybrid epoxy, and boron-epoxy composites. Those rods are substantially lighter than those of either fiberglass or bamboo. A typical graphite fly rod suitable for a Number 6 or Number 7 line weighs 1 1/3 oz. (40 gr). A casting rod blank will weigh about 25% more. Advanced composite rods have improved casting distances and accuracy, due to better vibration damping characteristics and improved response.

TABLE 2-27

Leading U.S. Manufacturers of Advanced

Composite Sports Equipment

Company	Archery	Fishing Poles	Golf	Racquet Ball	Tennis	Other
Aldila			X	X	X	
Babcock & Wilcox			X		X	
Carbonite/3M Co.		X	X			
Exxon/Graftek Leisure Products		X	X		X	Bicycle
Fenwick Products		X				
J. Kennedy Fisher Inc.		X				
Grafalloy Corp.					X	
Graphite Tech- nology Co.			X			
Lake King Rod Co.		X				
Lamiglas Inc.	X	X	X			Ski Poles
Research Engineer- ing Corp.		X	X			
Shakespeare/Columbia		X	X			
Skyline Industries		X	X			
Tremont Research Co.					X	

According to the American Fishing Tackle Manufacturers Association (AFTMA), the wholesale value of all fishing rods sold in the U.S. during the year ending July 31, 1977 was estimated to be \$82 million. Statistical data collected by the Association indicate that member firms of the association sold 7.3 million rods with a wholesale value of \$52.2 million. During the same period, thirteen member firms made fishing rods that contained at least 50% graphite fiber, and over 246,000 of these graphite rods were sold with a wholesale value of \$7.1 million. A detailed breakdown is given in Table 2-28. Graphite rods represented 3.4% of the unit sales of members of the Association, but 13.6% of their sales revenue. It is estimated that total U.S. sales of graphite fishing rods were 1.5 times the sales of graphite rods by AFTMA members, or about 370,000 rods with a market value \$10.7 million.

In spite of their high price tag, advanced composite fishing rods are becoming more popular, especially with experienced fishermen. The demand appears to be growing rapidly, and sales of graphite fishing rods may increase at a rate of 20% per year over the next 5 years. In 1983, sales of graphite rods could account for 25% of the wholesale value of all fishing rods sold in the U.S.

Many of the high price (\$70 to \$200 suggested list price) tennis racquets sold in the U.S. contain some small amounts of advanced composite materials. Leading producers such as Wilson, Slazenger, Dunlop, Bancroft and Head, among others, offer one or more tennis racquets that are selectively reinforced with advanced composite materials. Racquet ball and squash racquets are an expansion of the market. These racquets are not necessarily produced by the firm under whose label they are sold, but by specialty manufacturers such as those listed in Table 2-27.

A major sport where advanced composites have not made a major penetration is skiing. A certain degree of flexibility is required in the equipment used by the average skier, and a ski made of

TABLE 2-28

Fishing Rod Sales
for Year ending July 31, 1977
by Member Firms of
U.S. Fishing Tackle Manufacturers Association

Item	Units Sold	Total Wholesale Value (10^6\$)	Average Wholesale Unit Price,\$
Graphite* Casting Rods	115,999	3.15	27.16
Graphite* Spinning Rods	77,996	1.99	25.51
Graphite* Fly Rods	29,271	1.41	48.17
Graphite* Rods, other**	23,014	0.57	24.77
All Graphite* Rods	246,280	7.12	28.85
All Fishing Rods	7,300,000	52.17	7.15

* 50% or more graphite

** spin casting, and salt water rods

Source: Reference 78

advanced composites is too stiff. Some competition skis and water skis, as well as ski poles, have been made from advanced composites but these are minor applications.

During the past five years sporting equipment, principally golf shafts and fishing poles, provided the graphite fiber manufacturers with the minimum sales base which the industry needed to survive. Without this market, which consumed approximately 100,000 lbs/year (45 metric tons/yr) of fiber, advanced composites would have been even rarer and more expensive than they are now. This market will grow as new uses are identified or as new fashions develop, but no order of magnitude changes are expected.

It is to be noted that advanced composites are used principally in premium top of the line equipment which commands a retail price in excess of $100, and which is heavily promoted.

As a result it is believed by this author that the public perceives items made of advanced composites as being either a) expensive and exotic, or b) expensive and of good quality. The image thus far created for these materials may be an important factor in terms of their potential use in automotive applications.

2.4.3.2 Recreational Boats and Small Craft

Advanced composites are currently being used in the construction of recreational boats and small craft. Boats made from fiberglass reinforced plastics are designed with adequate stiffness as the limiting factor (79). Boats of equivalent stiffness but of lower weight can be obtained by replacing FRP with advanced composite structures. Because of its toughness and relative lack of brittleness, aramid (Kevlar 49^{R}) has been the high performance fiber most often used in this application. Aramid reinforced composite boats are lighter, more tolerant to damage, and less subject to vibration than FRP boats. Reducing the weight of power boats results in a faster boat with a given engine,

or in a more fuel efficient and economical boat of equal speed because a smaller engine can be used.

Small craft of many types have been built with aramid composites, and more than 40 canoe and kayak manufacturers now offer models with aramid fibers. Eight bass boat manufacturers offer aramid fibers as an option and one manufacturer reported that over 90% of his 1977 orders were for boats reinforced with aramid. In 1977 offshore power boat racing, aramid reinforced boats won 8 out of the 10 unlimited class races sanctioned by the Union International Motornautique. All key manufacturers of the offshore racing boats use aramid fiber reinforcement exclusively for serious entries to the unlimited class, but utilization in sail boats is fairly limited. Some championship boats have been built with Kevlar reinforcement such as the "Aquarius V", a Class C catamaran that won the Little America's Cup, "Joe Louis" that won the 3/4 ton Ocean Racing championship. Aramid hull construction is also being introduced into several class boats, such as the Flying Dutchman.

Most boom, spinnaker poles and battens of advanced composite materials weigh up to 50% less than comparable aluminum structures. Their reduction of weight aloft reduces wind pounding and heeling. Rigging made from advanced composites also presents a smaller aerodynamic shape and all of these factors result in a faster boat. A sailboat fitted with an advanced composite mast may be 0.1 knot faster than an equivalent sailboat fitted with a metal or fiberglass mast.

In spite of these technical advantages, advanced composites will not be extensively used as the spar materials of competitive sailboats because of a recent ruling by the Offshore Council of the International Rules Committee, to which the U.S. Yacht Racing Union subscribes. This ruling discriminates against advanced composites materials by applying a 1.03 rating factor (equivalent to a 3% time penalty) to a boat that uses spars made of a material other than wood, steel, aluminum or fiberglass (80). The rationale given for the ruling is to prevent an

undue escalation of the cost of ocean yacht racing which would result if all existing masts had to be replaced by advanced composite masts for a boat to remain competitive. The ruling cancels the technical advantage accrued from using advanced composite components in spars; however, the ruling does not effect use of composites in hull design.

Marine and marine accessories consumed approximately 155,000 metric tons of fiberglass reinforced polyester in 1977 (81). Assuming a 40% glass content, this is equivalent to 62,000 metric tons of fiberglass. It is not unreasonable to expect high performance fibers, principally aramid, to capture up to 2% of this market within the next five to ten years. This corresponds to an annual consumption of 1000 metric tons of high performance fibers. Dupont, the manufacturer of Kevlar 49[R], projects that the marine market will consume 40% of Kevlar 49 production in the mid 1980's.

2.4.3.3 Transport Aircraft

In the three years from 1973 to 1976, average prices for jet fuel paid by U.S. domestic airlines have risen from 12 to 31 cents per gallon, and from 12 to 43 cents per gallon for the U.S. international carriers. This resulted in a nearly 70% increase in direct operating costs, from about 0.9¢/ASNM (Air Seat Nautical Mile) to nearly 1.5¢/ASNM, during that period (82). Such fuel price and direct operating cost increases have caused an adverse impact on the economic health of the air transportation industry. Reducing the weight of an aircraft is one of the most effective ways of obtaining increased fuel economy, or increased aircraft productivity (payload).

Some characteristics of the principal commercial transport planes manufactured in the U.S. are given in Table 2-29. It can be noted that:

a) the ratio of payload to take off weight is about 0.20 for all these planes, and

b) that the fuel consumption increases with the take off weight of the aircraft.

Using advanced composites could result in a significant increase in payload, or decrease the fuel consumption of the plane. It is noted that the ratio of empty operating weight to maximum take off weight is about 50%. A 20% decrease in the empty operating weight results in a 10% decrease in the maximum take off weight, and this lower weight could be converted into either a 10% reduction in fuel consumption at equal payload or a 50% increase in payload at equal fuel consumption. Such modifications could have major economic impact on the operation of an airline.

To date, the use of advanced composites in primary and secondary structures of certified aircraft has, for the most part, been sponsored by NASA as part of their Aircraft Energy Efficiency Program or its predecessors. For the past ten years, NASA research has supported limited flight service programs in order that experience in the design, manufacturing, and operational performance of a variety of secondary aircraft components may be obtained.

A summary of flight experience obtained as of January 1, 1977 with advanced composite secondary structures on commercial transport aircraft is presented in Table 2-30. With the exception of the Boeing B-737 polysulfone spoilers, service experience of advanced composite structures in certified aircraft has been satisfactory. The polysulfone resin in the spoilers was found to have been attacked by "Skydrol" hydraulic fluid.

Although significant benefits should result from the extensive use of advanced composites in commercial airframe structures, the construction and operation of such an aircraft that makes extensive use of advanced composites entails major risks that the major aircraft manufacturers and airline operators were unwilling to undertake on their

TABLE 2-29

Major Characteristics of Commercial Transport Aircraft

Manufacturer	Boeing	Boeing	Boeing	Douglas	Douglas	Lockheed
Aircraft	B-727	B-737	B-747	DC-9	DC-10	L-1011
Date 1st Delivery	1962	12/67	12/69	6/65	11/72	4/72
Number Delivered by August 1976	1213	469	288	864	223	136
Average Annual Production Rate Through August 1976	86	54	44	78	64	34
Model Specifications						
Model No.	-200B	-200	-100	-30	-40	-1
Standard Passenger Capacity	163-189	115	385	105	225or270	273
Operating Weight Empty, kg	45360	29528	161855	25940	120678	109045
Maximum Payload, kg	17236	13562	76930	12743	46243	38373
Maximum Takeoff Weight, kg	83820	58740	332480	54884	251744	195045
Standard Fuel Capacity, Liters	30623	19547	178702	13925	135510	90140
Range at Maximum Payload, km	2685	3815	9136	3095	6845	5760
Empty Operating Weight / Maximum Takeoff Weight	0.54	0.50	0.49	0.47	0.48	0.56
Maximum Payload / Maximum Takeoff Weight	0.21	0.23	0.23	0.23	0.18	0.20
Fuel Consumption Index, Liters/km (Fuel Capacity/Maximum Range)	11.4	5.1	19.6	4.5	19.8	15.7

Source: Reference 83

TABLE 2-30

Commercial Flight Service of Advanced Composite
Secondary Structure Components
(up to January 1, 1977)

Aircraft, Material and Components	Total Aircraft	Number of Components	Start of Flight Service	Cumulative Component Flight Hours	Comments
Boeing B-707 Boron-Epoxy Foreflaps		2	1970	64000	No service problems
Lockheed L-1011 Kevlar 49-Epoxy Fairing Panels	3	18	Jan 1973	24000 (1/77)	No service problems, other minor impact damage
Boeing B-737 Graphite-Epoxy Spoilers	28	100	July 1973	700,000 (1/77)	No service problems, No visible damage
Boeing B-737 Graphite-Polysulfone Spoilers		10	Dec 1975 to Aug 1976	1000 (highest time component)	Removed from service after attack was noted with 3 spoilers
Lockheed L-1011 Graphite-Epoxy Floor Post	1	1		10,000 (1/77)	No service problems
Douglas DC-10 Boron-Aluminum Aft Pylon Skin Panels	3	3	Aug 1975	6500 (7/76)	No service problems No visible damage in high temperature environment (130°-350°F)
Douglas DC-9 Graphite-Epoxy Engine Nose Cowl Outer Barrel	1	1		1200 (1/77)	Some paint peeling initially observed. No service problems with properly prepared surface
Douglas DC 10 Upper Aft Rudder Graphite-Epoxy	3	3	June 1976	5200 (1/77)	No service problems

Source: Reference (84)

own. In order to alleviate some of the risk and accelerate the use of advanced composite structures in commercial transport aircraft, NASA initiated a comprehensive Composite Primary Structure Program as part of the ACEE Program. The specific objective of the program is to give U.S. commercial transport manufacturers the experience and confidence that will result in their making extensive use of advanced composites airframes. It consists entirely of contracts with the three principal manufacturers of large commercial transports, The Boeing Company, McDonnell Douglas Corporation and Lockheed Aircraft Corporation. Each of the contractors is being funded to develop and carry to the point of production commitment a minimum of two components covering the range from a small lightly loaded secondary structure to a medium size moderately loaded primary structure. Components currently included in the program are shown in Figure 2-9. Their principal characteristics are summarized in Table 2-31. Following FAA certification, components will be installed on production aircraft. The approximate schedule, including expected date of initial introduction into service for each of the components of Figure 2-9 is shown in Figure 2-10. Until January 1978, the program also included the development of a heavily loaded wing structure. This program has been postponed indefinitely until the potential hazard to electricl equipment associated with the dispersion of graphite filaments in the atmosphere is better defined. (See Section 3.5.5). A secondary reason for postponement of this effort was the hesitancy of the air frame manufacturers to make a firm production commitment for a major primary structure until the less critical structures that are currently being funded have been fully evaluated in service.

The aircraft structures being supported by the ACEE program are currently awaiting FAA certification. In addition, a number of other components developed by the airframe manufacturers are awaiting certification. These include a nacelle for the Douglas DC-9, and following Boeing Aircraft components: B-727 Engine Cowl, B-747 Aileron and B-747 Main Landing Gear Door. If FAA approval is obtained, these items are expected to go into production next year. According to industry sources, certification will be requested shortly for a B-727 composite

FIGURE 2-9 ACEE COMPOSITE COMPONENTS

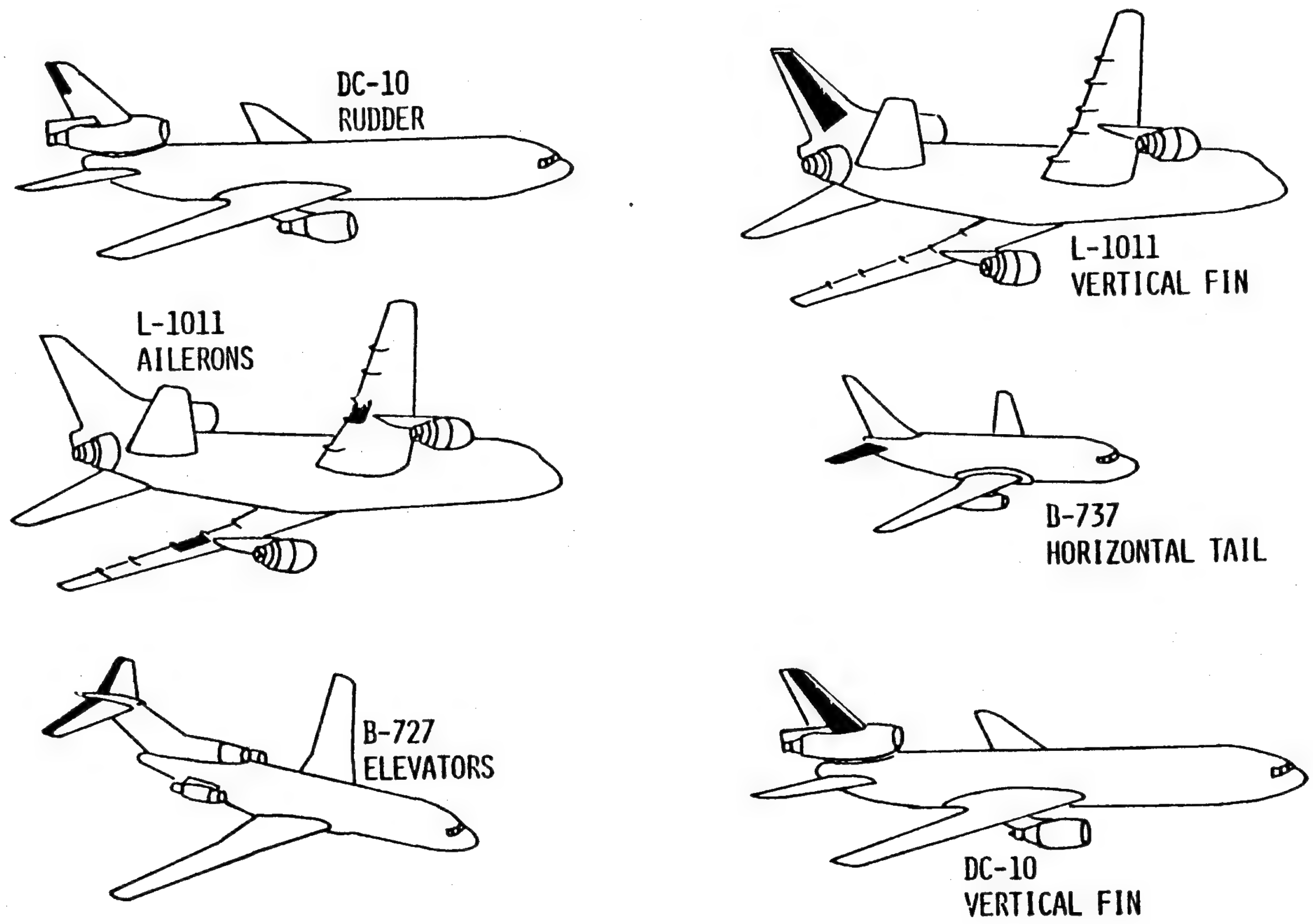
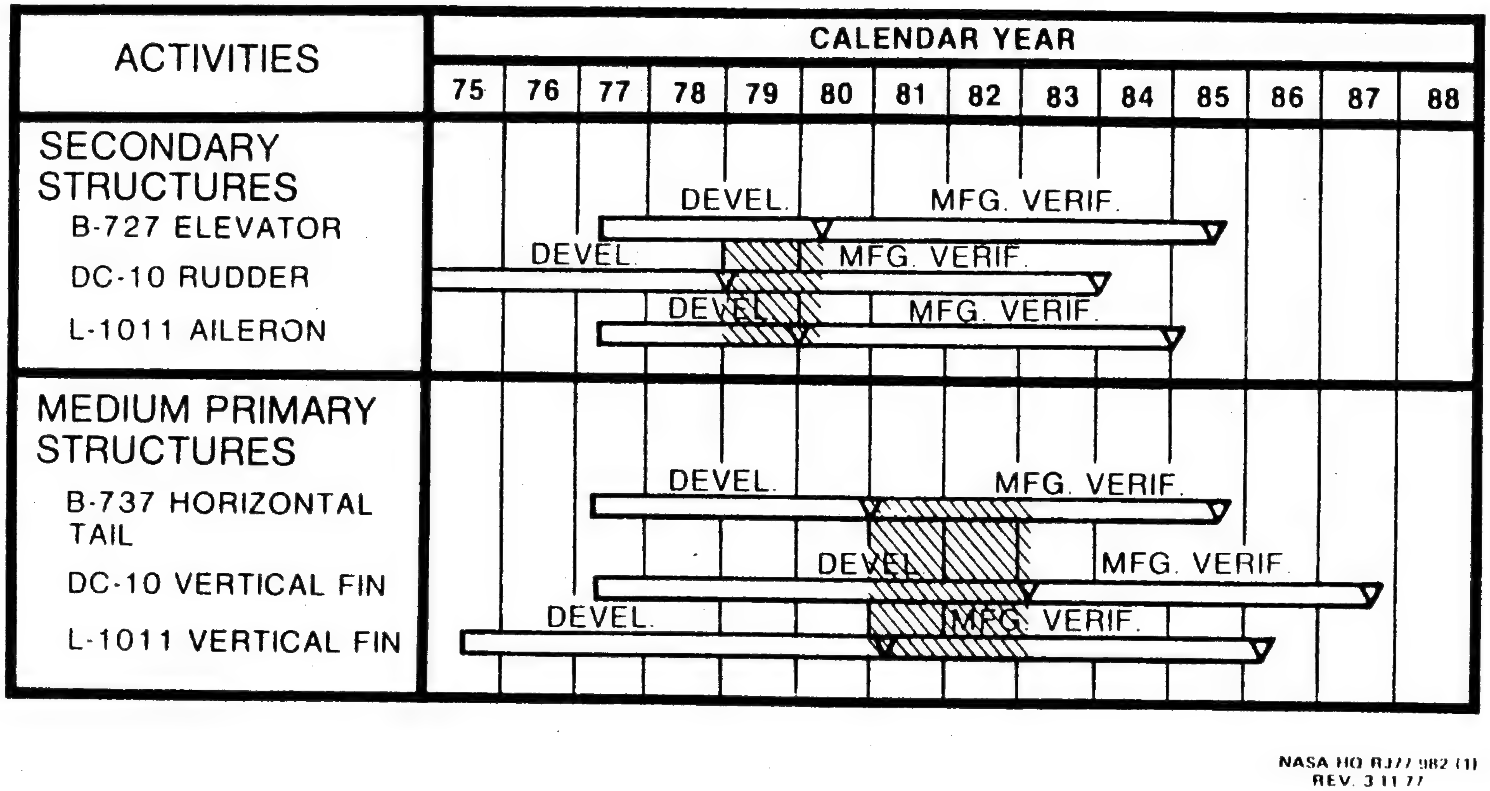


TABLE 2-31 COMPOSITE COMPONENT CHARACTERISTICS

	WEIGHT COMP/METAL (LB.)	PLANFORM AREA (FT.)	DIMENSIONS SPAN/CHORD (FT.)	
SECONDARY STRUCTURE				
727 ELEVATOR	196/278	54	19/3.3	2 PER A/C
DC 10 RUDDER SEGMENT	61/91	35	13/3.2	
L-1011 AILERON	109/140	32	7.7/4.2	2 PER A/C
MODERATE SIZE PRIMARY STRUCTURE				
737 HORIZONTAL STABILIZER	185/261	52	17/4.3	2 PER A/C
DC 10 VERTICAL FIN	1068/1282	114	27/6.5	
L-1011 VERTICAL FIN	1039/1230	150	25/9	

NASA HQ RJ77-2032A (1)
3-10-77

FIGURE 2-10 COMPOSITE PRIMARY STRUCTURES - MASTER SCHEDULE



rudder that is also being developed on company funds.

In addition to the above, more extensive use of advanced composites is expected on a new model of the L-1011 that is scheduled to go into service next year (86), and in this manner reduce the weight of the aircraft by 2.5 tons. This will entail converting all 79 fairings on the aircraft from fiberglass-epoxy to aramid-epoxy composites; and converting floor beams and floor posts in the hold from aluminum to graphite-epoxy. In addition, it should be noted that aramid-epoxy composites will continue to be extensively used in interior trim applications such as overhead storage racks and ceiling panels.

It is possible to reduce the weight of a DC 10 by 2400 lbs. (1100 kg) by substitution of advanced composite for metal or fiber-glass reinforced plastic in the following components: trailing edge panels, rudders, elevators, ailerons, fairings, fan cowl door, nose gear door, floor beams, and spoilers (87). Advanced composite elevators and rudders are currently being developed under the ACEE program. The early 1980's will see the development of some of the advanced composite secondary structures mentioned above.

This component activity will result in a significant increase in consumption of advanced composites in transport aircraft in the near future. Over the next five years, annual graphite fiber consumption by the three major commercial airframe manufacturers should increase from 10,000 lbs (4,500 kg) in 1977 to 60,000 lbs (27,000 kg) in 1980, to as much as 180,000 lbs (81,000 kg) in 1983. In the long term, high performance fiber needs of commercial aircraft manufacturers could increase by one or two orders of magnitude. Based on the data presented in Table 2-29, it was calculated that the average empty weight of commercial airplanes produced in the U.S. in the early 1970's was 72,000 kg. It can be assumed that with advanced composites, the weight of this plane could be reduced by 20%, or 14,000 kg. If it is assumed that 40% of the weight of the aircraft is made of advanced composite (and 60% of the advanced composite weight is

fiber), approximately 14,000 kg of high performance fiber would be required per aircraft. Based on an average annual production of 360 aircraft (obtained from Table 2-29), the projected total fiber consumption would be approximately 5,000 metric tons per year, or 11 million pounds per year, or approximately 100 times current consumption.

It is unlikely that there will be extensive use of advanced composites in primary structures of commercial aircraft by 1990. However, it is not unreasonable to consider that extensive use of advanced composites will be made in secondary structures which could represent 10% of the structural weight of the airplane, or about 5% of the current weight of an aircraft. This would result in a consumption of about 2,200 kg of high performance fibers per aircraft. Assuming the same annual aircraft production as above, a total fiber consumption of about 800 metric tons/year, or about 1.7 million lbs/year, by the year 1990.

2.4.3.4 General Aviation

In 1977, U.S. manufacturers shipped 16,904 business and utility aircraft that had a total value of $1.49 billion. None of these contained advanced composite materials in flight structures. There is however current development activity, with the degree of involvement and interest varying from intense to non-existent.

Intensive use of advanced composites is envisioned by Lear Aviation Inc. of Reno, Nevada. This company is designing a prototype turboprop plane that will have an all composite primary structure. The fuselage, wings, tail, control surfaces and propellar will be made entirely of advanced composite materials, principally graphite-epoxy composite. The twin turbine plane, in the seven passenger executive class, will be known as the Lear Fan. Its basic empty weight will be 3,500 lbs (1,600 kg) and its gross weight will be 6000 lbs (2700 kg). It will have a maximum range of 2750 statute mile (4400 km) with 45 min. reserve, with a normal fuel capacity of 250 gallons (945 liters), giving a fuel economy

(with reserves) of 11 mpg (4.65 km/ℓ). Comparable turboprop aircraft currently on the market have fuel economies of 4 to 6 mpg (1.7 to 2.3 km/ℓ). This remarkable improvement in fuel economy is not solely due to the use of composites since the plane incorporates many other novel design features, including an unusual pusher propeller and empennage configuration. The company is currently building a demonstration aircraft in order to obtain FAA certification this summer and hopes to enter production late this year. A production level of over 300 aircraft/year is anticipated by 1981, and the plane will sell for $800,000. It is estimated that if composites had not been used, the aircraft would have weighed an additional 600 lbs which would have reduced its seating capacity by 3 passengers and increased fuel consumption by 10%.

Cessna Corp. of Wichita, Kansas, with some NASA support, has been studying the application of advanced composite materials to light aircraft structures, and to some interior structures. Components currently being examined include propellers and various control surfaces for the Citation III business jet aircraft. Cessna also recently announced that in 1980 it will offer a new four place twin engined aircraft, the Model 303, which will make extensive use of bonding and composite materials (88), but the company has not yet released details concerning this aircraft.

Grumman Corp. of Bethpage, N.Y. is studying the potential use of advanced composites on its Gulf Stream III. Other companies such as Piper Aircraft Corp., presently consider the use of any high performance advanced composites to be economically prohibitive and do not foresee any significant use until finished product cost is commensurate with present costs (89).

2.4.3.5 Automotive Transportation

Passenger Cars: Fuel economy and light weight vehicles have become vital concerns of the automotive industry because of the Energy Policy and Conservation Act that was passed into law on December 22, 1975. This legislation mandates a production-weighted

corporate average fuel economy (CAFE) for passenger automobiles that increases from 18 mpg in 1978 to 27.5 mpg in 1985, and it is likely that these requirements may become even more stringent in the post-1985 period. The fuel economy of nonpassenger autos with a gross vehicle weight of less than 8500 lbs will also be regulated, and by 1981 will have to be at least 15.5 mpg for four wheel drive vehicles, and 18 mpg for two wheel drive vehicles. Current regulations have not concerned themselves with heavy trucks and buses, but with those vehicles, economic circumstances associated with rising fuel costs dictate that they be fuel efficient. Reducing vehicle weight and fuel consumption result in lowered operating costs and in increased hauling capacity.

The requirement of 27.5 mpg in 1985 will require not only that the average weight of automobile be reduced from 4000 lbs (1800 kg) to 3100 lbs (1400 kg), but will also require major gains in power plant efficiency and packaging optimization, if the general attributes - space, ride, comfort - of American automobiles are to be maintained. General downsizing of all automobiles is not an attractive option to the manufacturer because it entails a major marketing risk (Would small cars sell as readily as current larger cars?) and because small cars are less profitable than large cars (90).

In order to reduce vehicle weight and still maintain sales attributes, automotive structures and materials are being closely examined. Greater use is being made of materials such as high strength low alloy (HSLA) steels, aluminum, and both fiberglass reinforced and nonreinforced plastics. With extensive use of these materials, it should be possible for the manufacturers to produce an automobile that will meet the 1985 CAFE requirements and still find market appeal.

The manufacturers are concerned about the likelihood that the fuel economy regulations after 1985 will become even more stringent. It would be difficult to meet the increased CAFE requirements with current materials technology without a significant level of downsizing. In the longer term, they are examining the potential of high performance

advanced composites as a means of achieving significant weight reduction.

Research interest in automotive applications of advanced composites materials started in the early 70's. The interest intensified with the increases in the price of petroleum fuel and energy legislation. Currently, all the major automotive manufacturers have active development programs investigating the potential use of advanced composites in automotive structures, and a wide variety of prototype automotive components have been made out of advanced composite materials, such as hinges, brackets, leaf springs, drive shafts, doors, door guard beams, etc. Materials used have included graphite, aramid, and a variety of hybrid resin (mainly epoxy) composites. Approaches have included the reinforcement of metal with organic composites but little has been done with metal matrix composites. Many of these components have been tested in actual service over the past few years and have been found to perform well.

The current status of automotive uses of advanced composites can be summarized as follows:

a) parts that are the equivalent of steel parts in performance but significantly lower in weight have been built;

b) these parts have passed a variety of laboratory tests successfully,

c) they paint well, and

d) it's possible to reconfigure existing structures because one can design the desired degree of stiffness into a component.

Ford Motor Company has publicized its interest and activity in applying advanced composite materials to automotive structures to a much greater degree than the other manufacturers. The Ford Light Weight Vehicle (LWV) program is the curb stone of its current research

activities in this area. The company is currently building a prototype automobile that uses graphite composites to as great an extent as possible but which will retain the appearance and performance characteristics of the Grenada, an intermediate size six passenger automobile. This prototype will be on display at the 1979 SAE Exposition in Detroit, Michigan.

The Light Weight Vehicle will have a curb weight of 2517 lbs (1143 kg) and an inertia weight of 2750 lbs (1250 kg), or 1250 lbs (657 kg) less than the standard Grenada. Because of lower structural weight, a smaller engine, a 2.8ℓ V-6 instead of a 5.8ℓ V-8, can be used without changing performance (0-60 mph, (100 km/hr) in 12 sec). Fuel economy (metro/highway) increases from 17 mpg for the standard Grenada to 23 mpg for the LWV. In summary, substituting graphite composites for steel in this automobile results in a 31% reduction in inertia weight and a 35% increase in fuel economy.

The cut-out of the LWV auto, shown in Figure 2-11, highlights the graphite containing components. The effect of substituting graphite composite for steel on the weight of specific components is shown in Table 2-32.

Ford Motor Company considers the LWV program to be both a learning and educational tool. By having built as many of the components of an automobile out of advanced composites as possible, it will have learned which of these can be most readily adapted to the technology and will have been exposed to potential manufacturing problems. The program is also an educational tool in that it will demonstrate to automotive designers and production engineers, both within and outside the company, that a "normal" automobile can be made from advanced composite materials. For this reason, the LWV was designed to a standard configuration, rather than to one which would make optimum use of advanced composites and which might appear "exotic" or "futuristic."

A number of problems and issues have to be addressed and solved in order for advanced composites to be considered

FIGURE 2-11

FORD LIGHTWEIGHT VEHICLE PROGRAM

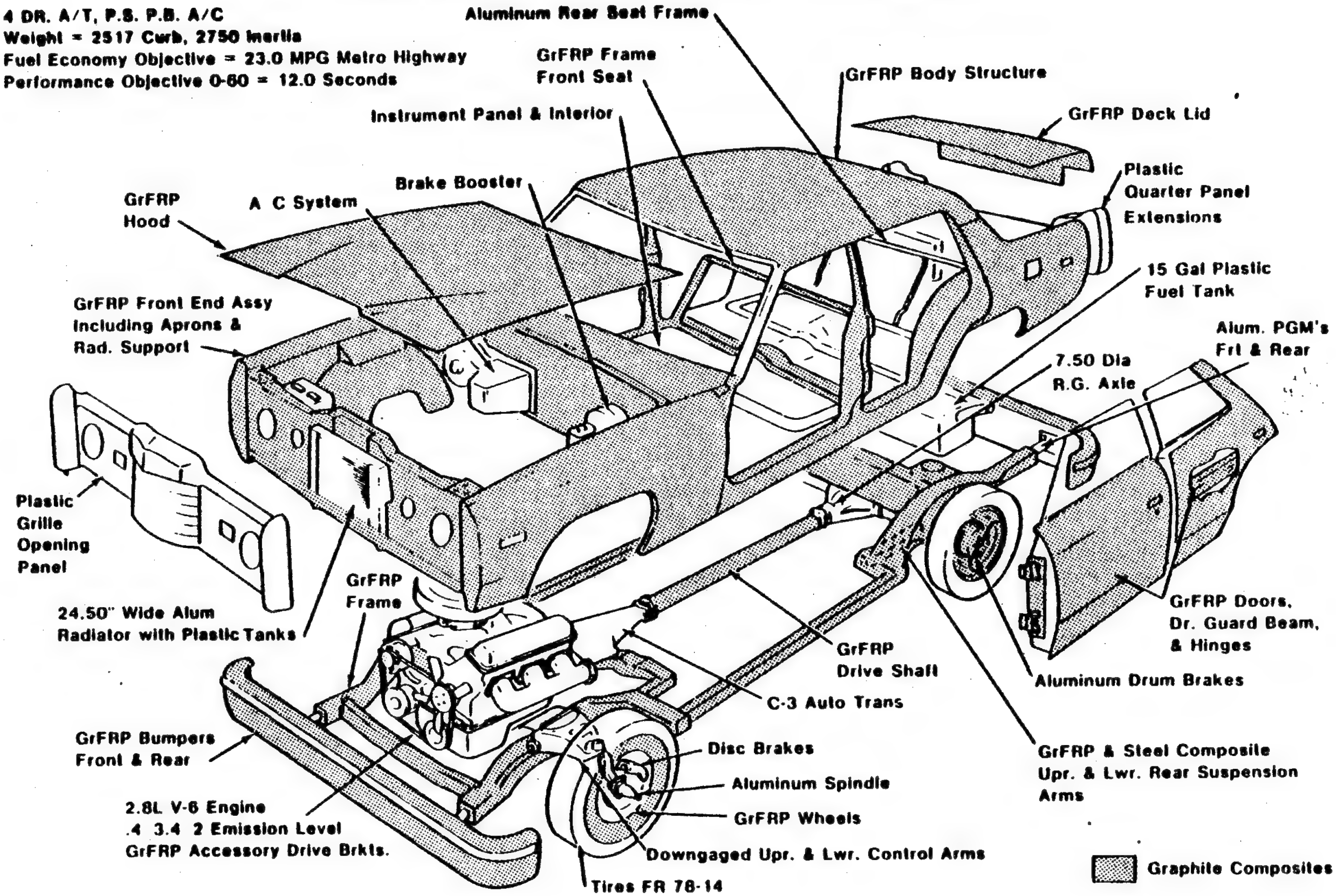


TABLE 2-32

Ford Lightweight Vehicle Program
Graphite Component Weight Summary

	Steel	Graphite	Reduction
Hood	40.0 lbs.	15.0 lbs	25.0 lbs.
Door, R.H. Rear	30.25	12.65	17.60
Hinge, Upper L. H. Front	2.25	.47	1.78
Hinge, Lower L. H. Front	2.67	.77	1.90
Door Guard Beam	3.85	2.40	1.45
Suspension Arm, Front Upper	3.85	1.68	2.17
Suspension Arm, Front Lower	2.90	1.27	1.63
Transmission Support	2.35	.55	1.80
Driveshaft	17.40	12.00	5.40
Air Conditioning, Lateral Brace	9.50	3.25	6.25
Air Conditioning, Compressor Bracket	5.63	1.35	4.28

Source: Ford Motor Company

as materials of construction for production automobiles. These include:

a) Cost of raw materials. At current prices, advanced composites are prohibitively expensive for nearly all automotive uses. Specific applications would become attractive at graphite filament prices of less than \$10/lb, and many applications could be considered if filament price dropped to \$5/lb.

b) Manufacturing. Most of the experimental advanced composite automotive components have been made with aerospace fabrication techniques that are too expensive and too slow to be considered for high volume automotive applications. It will be necessary to adapt, and improve upon, existing fiberglass reinforced plastic manufacturing technology. The conductivity of graphite filaments will require that provisions be made for containing these fibers during shipping, storage, and manufacture of composite structures. There may also be some assembling problems with advanced composites. Advanced composites do not yield as metals do, and therefore cannot be pounded into place. This may require large automotive structures to be fabricated to much closer tolerances.

c) Durability - there has been no demonstration that advanced components can survive 50,000 miles (80,000 km) of actual automotive use.

d) Damageability - the failure mode of advanced composites which are brittle materials is very different from the failure of metals which can yield. Composites are less likely to deform under light loads than metals, but can shatter and form jagged edges upon severe impact in some cases, or simply delaminate in other instances.

e) Crashworthiness - see Section 3.12.2.

f) Repair Upon Damage - The ability of being able to repair major structural components made of any reinforced plastic is

an open issue. It would be desirable to be able to repair rather than replace large components.

g) Noise Vibrations and Handling - The road handling characteristics of a large, low weight automobile are not known at the moment and it may be necessary to include load leveling provisions into the design of an automobile.

h) Recycling - Reinforced thermosetting resins can not be economically recycled at the moment, so that land fill of scrap advanced composite parts is the only current available option.

Future development work will address itself to these issues. Current costs are not a major consideration because of the leverage of the automotive industry. The average use of only 1 lb of graphite filament per automobile will create a demand for 10 million lbs. of graphite a year. At this level, graphite could be sold for less than $10/lb (see Fig. 2-7). The cost of graphite (or aramid) will be further diluted by extensive use of hybrid composites.

Developments over the next few years will focus on manufacturing technology and proof testing of selected components in actual service. Applicable manufacturing technology was previously discussed in Section 2.3.4.3. One or two selected advanced composite components will be introduced by the major manufacturers in a limited production automobile or light truck in either later in model year 1979 or in model year 1980. The first use of advanced composites will be in non-safety critical parts that can be easily removed, such as an air conditioning support bracket. It is quite likely that the first production use of advanced composites by General Motors Corp. will be on the Chevrolet Corvette (91).

Over the next few model years, additional advanced composite parts will be introduced for service evaluation if no difficulties are encountered in the first series. Most of these parts will be

structural parts that will weigh less than 5 lbs (2.3 kg). A graphite reinforced hood or deck lid may be included to evaluate an external painted part. By 1985, there may be as many as 10 parts in service on 10% of the vehicles produced. Assuming an average weight of 3 lbs per part, a 20% graphite content, and the production of 10 million autos, this corresponds to a demand of 600,000 lbs (273 metric tons) of graphite fiber by the automobiles in 1985.

Advanced composites usage in automobiles beyond 1985 will depend mainly on CAFE requirements imposed on the manufacturers. If these do not become much more stringent than 27.5 mpg, (i.e. less than 30 mpg) use of advanced composites will remain limited to brackets, hinges and a variety of similar small parts that will find general application, and to larger components for selected automobiles. By 1990, the combined weight of the small components in an average car could be as much as 10 lbs. to 20 lbs. Again, assuming a 10 million car/year production rate and a 20% graphite content, a graphite fiber consumption of 20 million to 40 million lbs/year is envisioned.

Advanced composites will also be used to transfer automobiles from one inertial weight category to a lower one. For example, currently for EPA test purposes all automobiles that have an actual inertia weight (curb weight + 250 lbs) of 2751 lbs to 3250 lbs are grouped in the 3000 lbs inertia weight class; those that have an inertia weight of 3251 lbs to 3750 lbs are grouped in the 3500 lb inertia weight class, etc. The reported fuel economy of a vehicle is a function of its inertia weight and varies as the 0.6 power of the inertia weight (92). Thus a vehicle that has an inertial weight of 3249 lbs will have a much better EPA fuel rating than a comparable vehicle that has an initial weight of 3251 lbs. The first vehicle, which will be tested in the 3000 lb class will have a rated fuel economy that is 10% higher than the second vehicle which will be tested in the 3500 lb class, and this difference could be as much as 2 to 3 mpg.

In the future, EPA will narrow the bandwidth of the

inertial weight classes to 125 lbs which will reduce the incentive to drop from one weight class to another by a factor of 4. In 1985 the difference in apparent fuel economy would be 0.8 to 1.2 mpg. Given the structures of the law ($5/automobile for every 0.1 mile CAFE), a one mpg improvement in fuel economy in a production run of 100,000 automobiles, is worth $5 million. Under these circumstances, replacing a steel component with a graphite component has a value well beyond the costs of the components. A weight savings of 10 lbs/car can be construed to be worth $5/lb of weight saved.

This situation may arise in only a small percentage of the vehicles produced. Assuming the use of 30 lbs of hybrid composites to save 10 lbs of vehicle weight, on 5% of the fleet, an additional graphite usage of 3 million lbs/yr is calculated.

If the CAFE requirements become significantly more stringent than 30 mpg in the post 1985 period, then advanced composites will find much more extensive use in the automotive industry, particularly in larger luxury vehicles.(*) For example, increasing CAFE will not have much impact on the use of materials in small vehicles that would already be fuel efficient; however large automobile would be vulnerable to a higher CAFE unless high performance composites would be used extensively. Approximately 8 to 10% of the current new car market is for luxury vehicles that sell for more than $10,000 apiece. The market for these status vehicles will continue to exist, nearly irrespective of the price of the vehicles (within limits of course). It is estimated that the average automobile in 1990 will consume 150 lbs of reinforced polyester plastic (93). It is not unreasonable to assume that the larger luxury vehicles may make more extensive use of reinforced polyester than the average car, and that the reinforcement may include significant amounts of graphite. If it is assumed that the luxury car will contain four times as much reinforced polyester composite as the average car, or 600 lbs, and that the graphite content is 20%, the larger vehicles would contain an additional

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(*) This idea was suggested by Dr. Joseph N. Epel, Director, Budd Plastics Research and Development Center.

120 lbs of graphite filaments. These would add $800 to $1000 (constant dollars) to the cost of the car. While this added cost would be prohibitive in an average $4000 automobile, it could be considered as providing optional luxury and space in a $12,000 status vehicle. The owner of a matched set of graphite golf clubs will consider a graphite composite automobile to be an accessory needed in order to drive to the country club in appropriate style. A million luxury automobiles a year, each containing 120 lbs of graphite filament, would consume a total of 120 million pounds of graphite filaments a year.

Electric vehicles would be another group of automobiles in which advanced composites would be used extensively. Increasing the weight of the chassis and body of a vehicle by a given amount is more detrimental to an electric vehicle (EV) than to an internal combustion engine (ICE) vehicle. This is due to the fact that the weight of the power generating group (motor and fuel or battery) is a much greater fraction of the gross vehicle weight for an electric vehicle than for an ICE vehicle. Furthermore, the unit cost of the power generating group is much higher for an EV than an ICE vehicle. Weight reduction is three times as valuable in an electric vehicle as in an ICE (94). At the moment, there are few EVs in service, but DOE is funding a demonstration program which will result in 10,000 EVs being in service by 1986. An optimistic projection would assume an order of magnitude increase in EV population by 1990 which corresponds to a production rate of 25,000 vehicles a year. It is estimated that an EV could consume 600 lbs to 800 lbs of advanced hybrid composite in its body and chassis components. This EV production would consume approximately 3 to 4 million pounds a year of high performance fiber.

The truck and bus market is a derivative market of the passenger automobile market. Because of the lower production rates, better maintenance received, and the direct economic value of weight savings to the purchaser, advanced composites may be introduced into truck production more readily than automobile production. The same general components that would be used on automobiles would also be used on trucks.

Some larger components that would be used on heavy trucks would be springs, drive shafts, and reinforcement beams, and possibly some body panels, such as hoods. For example, a 125 lb steel leaf spring for a heavy truck can be replaced by a 30 lb. graphite epoxy leaf spring that has better fatigue life and higher load capability. On an experimental basis, it has been possible to replace a two piece steel drive shaft by a one piece graphite epoxy composite drive shaft that eliminates the weight and cost of a center main bearing.

Historically, approximately 5% of the reinforced plastics used in transportation has gone into truck and bus construction. It is expected that advanced composites would follow this general trend on the long term. In the near term (before 1985), the ratio may be higher, but no more than 10% of automobile consumption.

Based on the above discussion, the total projected consumption of high performance fiber by the automotive industry in 1990 is estimated to range from about 30 million to slightly over 150 million pounds per year (15,000 to 75,000 metric tons/year). This market would dominate the consumption of high performance fibers.

2.4.3.6 Agricultural Machinery

Farming is essentially a series of unit operations that have to be carried out over a precise schedule, with only a narrow time window available for each operation. Each specific operation has to be successfully executed when due. There are severe economic penalties for not doing so - a poor yield or failure of the crop. Given the uncertainties of climate and weather, a farmer cannot afford to have a critical piece of equipment fail or be inoperative when it is required, and thus he places a high premium on equipment reliability and on ease of repair.

Manufacturers of agricultural equipment are evaluating

the potential of advanced composite components as a means of decreasing the cost or of increasing productivity of farm equipment. Applications include components for self propelled equipment similar to the truck components discussed in the previous section, namely drive shafts, leaf springs, support brackets, etc. Since traction increases with increasing system weight the motivation for using advanced composites is not weight saving but lower manufacturing costs or better equipment performance in terms of longer life, better fatigue characteristics, higher reliability, lower maintenance, less corrosion, reduced inertia for better energy transmission, and less noise.

Advanced composites are also being considered for use in a variety of drawn equipment, such as seeders, tillers, and harvesters. In terms of mechanized U.S. farming operations, the larger the machinery, the higher the acreage that can be worked within a given period of time and with a given amount of human labor. The width of many pieces of current agricultural machinery is currently limited by the weight of the machinery. The ultimate width of a piece of drawn machinery is determined by either the pulling capacity of the tractor that the farmer has available, or by the load bearing capacity of the soil. If the equipment is too heavy, it will sink into the soil and not perform properly. For example, the widest piece of equipment made by one of the leading agricultural equipment manufacturers, is a 31 ft (9.4 m) wide 12 row crop cultivator. Harvesting platforms are 24 ft (7.2m) or less in width. It is possible to conceive of equivalent equipment made of advanced composites that would be two or three times as wide and weigh no more, or even less, than present equipment made of steel. Availability of such equipment would allow a farmer to process twice to thrice the acreage within a given period of time. The equipment would be modular or foldable to allow passage over public roads.

There is a tendency towards one till or no till farming in the U.S. There is a requirement for equipment that performs more than a single operation at a time. Multifunctional equipment is

weight constrained. In order to have the depth needed to place the various tools, the width of the equipment is reduced. With advanced composite components, wider equipment could be made. With this sort of equipment, a farmer could operate a larger farm without increasing labor requirements, or use it to minimize the risk of operating a farm of given acreage. By being able to process more acreage in a given period of time, a farmer effectively increases the size of the temporal window constraining a given operation. For example, if five days are available for seeding, and a farmer can plant the seed in 2 days, rather than in four days, a rainstorm on the third day that washes away the seed planted on the previous two days, has very different consequences. The farmer who can plant in two days can replace all the lost seed. The farmer who needs four days will be able to plant only half his acreage. Similar reasoning can be applied to harvesting of the crop. Availability of this type of equipment could have major impact on farm productivity.

The use of advanced composites in components for self propelled equipment will follow apace of their use in heavy duty trucks. The use of advanced composites in harvesting equipment is currently at the preliminary exploratory design stages and would not be in production for a decade. Many of the barriers to the production use of advanced composites in automobiles are also applicable here. Wear resistance is an additional important requirement in this instance since the equipment is to be exposed to much rougher service.

2.4.3.7 Material Handling Equipment

The problems and opportunities for advanced composites in material handling equipment (such as bulldozers and forklift trucks) are similar to those encountered in agricultural equipment because the two classes of equipment are very much alike. Mobile cranes and aerial ladders are a special category of equipment wherein advanced composites could be applied advantageously. In this instance, weight reduction increases the mobility of the equipment, and for example, cranes with larger booms could be built without increasing the gross vehicle weight.

2.4.3.8 Industrial Machinery

Advanced composite components are currently being evaluated for a broad range of industrial machinery which have high speed moving parts. Textile machinery has been the focus of much attention. The use of graphite composites on various components of fly shuttle weaving looms has increased the performance of the looms. The benefits of light weight, stiffness, fatigue resistance, and noise reduction have led to higher productivity and reduced downtime. Picking sticks are the levers that drive shuttles back and forth in fly shuttle weaving looms. Picking sticks which are currently made of densified wood often fail after three to six months operation. Experimental picking sticks made of pultruded graphite weighed 65% less than wood, which resulted in a 10% increase in loom speed and an operational life of up to three years; additionally, a noise reduction of 3 dBA was also reported (95). Other textile machinery components under development include heddle frames, lay bars, flyer arms, needles, sinkers, guide bars, and faller bars. However the acceptance of these developments by the textile industry has been slow, in great part, due to the depressed conditions of this industry and its hesitance to invest in new technology when currently, increases in production capacity are not required. Similar industrial development applications include arbors for cigarette packaging machines, components of paper making machines, and copying machines.

These composite parts will be introduced slowly over the next decade as replacements for components made of standard materials but total consumption of high performance fibers is not expected to be large. This projection would be sensitive to changes in regulations pertaining to noise in the workplace, and, if OSHA noise regulations become more stringent, advanced composite components would become more valuable, as they offer a means of significantly reducing (3 dB to 5 dB) the noise of large machine systems.

2.4.3.9 Abrasive Tools

The abrasive properties of boron fibers are receiving

increasing attention. Barnes Drill Company of Chicago, IL is marketing a honing tool that uses 5.6 mil boron as the abrasive. General Dynamics Corp. and a number of smaller companies are developing boron filament core drills and similar tools. In this application, boron filament composites compete with particulate composites of abrasive materials such as diamonds, cubic boron nitride, alumina, and silicon carbide. The shortcoming of particulate abrasives is the geometric limitation of approximately equiaxial particle shapes that have a tendency to "pull out" as the matrix is worn down. This limits the cutting speed of the tool and the pressure with which it can be applied to the workpiece. The boron filament form overcomes this limitation and exhibits greater resistance to pull out. Furthermore, the high compressive strength of boron allows the tool to be applied with greater pressure.

This development will be important in applications where cutting speed and wear resistance are critical considerations, such as in rough machining operations. Oil and gas drilling tool bits could be an important outlet for boron composite abrasive tooling. In this application, the costs of drilling a well are proportional to the time required. Boron tool bits could reduce overall drilling time in two ways; increasing the rate of drilling per se, and reducing the number of times drilling operations cease in order to replace the drill bits. At the present time, this development is under the cloud of patent litigation, and until the parties involved have resolved their differences, further commercialization and proof testing will be restrained.

This appears to be an excellent application of boron, and potentially also of silicon carbide and alumina fibers, which could greatly improve the productivity of many rock cutting operations.

2.4.3.10 Chemical Plant Structures and Equipment

Advanced composites are starting to find specialized uses in chemical plant process equipment where corrosion resistance is of

prime concern. For example, a graphite fiber reinforced polyphenylene sulfide (PPS) valve was commercially introduced last fall by Babcock and Wilcox Co., Advanced Composites Department. The valve can be used interchangeably with alloy valves in piping systems for severely corrosive fluids - most bases and many acids in diverse concentrations - with temperatures from $-40^{\circ}F$ to $300^{\circ}F$, and at line pressures of up to 200 psi. International Polymer Corp. makes graphite PPS bearings, piston rings, and similar equipment that are also used in the chemical industry.

The use of fiberglass reinforced plastics (FRP) in the processing, transmission and storage of corrosive chemicals is well established and documented. FRP has served well in environmental protection and pollution abatement equipment, such as scrubbers and neutralization tanks, and in platforms, walkways, and safety railings, in petroleum refiners and chemical plants. Currently about 10% of all FRP is consumed in such corrosion resistant applications (81).

The design of the larger pieces of equipment is controlled by the stiffness of the FRP. In some instances, selective reinforcement of the structure with graphite fiber could be cost effective even at current prices for graphite. As the price of graphite decreases to less than $20/lb, the use of graphite/glass hybrids will increase chemical plant structural equipment. Graphite composites will also find use in environments where FRP fails, particularly highly caustic solutions which attack and dissolve the glass fibers.

Since the use of advanced composites in chemical plant structures and equipment will be an evolution of existing FRP technology, development time will be compressed, and the pacing items will be the cost of the high performance fibers. Uses of hybrid composites will be established within the next five years, and by 1990, graphite consumption should be of the order of 10% of the FRP consumption for corrosion resistant applications which is projected to be 500 million lbs (230,000 metric tons) in that year, assuming an annual growth rate of 8%. The corresponding graphite fiber consumption in 1990 would be 50 million pounds (23,000 metric tons).

2.4.3.11 Medical Applications

A number of interesting medical applications of advanced composites have been investigated and developed such as radiological equipment and external and implantable prosthetic devices.

The acknowledgement that dangerous side effects can occur to human beings when subjected to excessive radiation doses has required that medical equipment limit the amount of patient exposure to X-rays. Any type of material between the patient and the film recording the X-ray will absorb some portion of the X-rays and increase the dosage level that must be applied to the patient to get a clear X-ray view. Structures between the patient and film include film cassette holders and patient support devices. In order to have sharp, focused radiographs, these components are required to be stiff and exhibit minimal deflection under the patient load, yet must also be as thin as possible to minimize X-ray absorption. Graphite-epoxy composites are fairly transparent to X-rays because of the low atomic number of carbon. This property, combined with their high structural integrity and stiffness, makes graphite composites an excellent choice as a structural material. Angiographic compression plates are currently being manufactured with graphite fiber composites, as have body support structures such as therapeutic X-ray table tops and computed tomography body scanner patient support couches (90).

Radiographic table tops and related equipment are currently being made with graphite-composites by a number of European firms, such as Philips in the Netherlands, and Siemens Corp. in West Germany. U.S. medical X-ray manufacturers that are becoming seriously interested in manufacturing this equipment include the U.S. affiliates of these firms, as well as Picker Corp. of Cleveland, Ohio, General Electric Company, Medical Systems Division of Milwaukee, Wisconsin, and Litton Medical Systems of Des Plains, Illinois. According to industry sources, a market of 200-300 large table tops per year is seen for this equipment, and some additional units might be required if existing installations are to be modified.

The Veterans Administration is currently funding the Browning Manufacturing Co. to make prototype graphite/epoxy components for artificial legs. These include heels and ankle assemblies. Preliminary results have been encouraging, but significant further effort is required to reach production stage. External prosthetic devices appear to be a natural application of advanced composites.

Carbon-carbon composites may be a useful material in a variety of transcutaneous applications. Pyrolitic graphite has been found to be biocompatible with the human organism, is clinically accepted, and is currently used in the construction of cardiovascular prosthetic devices (97). The main drawbacks of pyrolitic graphites are its mediocre strength and brittleness. Carbon fiber reinforced carbon (CFRC) shows much improvement in these properties, and being wholly made of carbon, remains biocompatible. Medical applications have been explored in Cardiff, Wales, and in Brazil in close association with various hospitals in Sao Paulo. Two clinically successful applications have been CFRC pins for bone adjustment and heart valves (98). Potential applications of CFRC that have been proposed include the fixation of artificial limb extensions to the stump of amputated limbs, total joint replacement, especially hip arthoplasty, and dental implants (artificial tooth roots) among others.

More mundane medical applications of advanced composites being considered include lightweight mechanical supports and equipment for orthopedic and handicapped patients. These include wheel chairs and braces. Other potential uses of advanced composites would include crutches or casting formulations. It is current orthopedic practice to use FRP casts instead of the traditional much heavier plaster of Paris casts. Plaster of Paris casts are still used where a high degree of rigidity is desired, for example in a "mobile" leg cast of a heavy patient. Graphite composite could be used to make a truly "mobile" lightweight cast of required rigidity.

2.4.3.12 Scientific Instruments

The same properties that make graphite-epoxy composites valuable for components of satellites and space instrumentation systems are also used to advantage in earthbound scientific instruments. Extensive environmentally controlled facilities are often built to minimize temperatures, flexure and vibration induced errors when precision measurements are required, and the use of graphite-epoxy composite structures could minimize the need for controlled environmental chambers. Examples of instruments constructed out of graphite-epoxy components include a tubular inside micrometer which has demonstrated an order of magnitude improvement over a standard metal version.(95) Optical benches made from graphite epoxy composite are not only much lighter structures than standard benches that use heavy granite bases but they also do not require environmentally-controlled test chambers which are often more expensive than the instruments they house. Graphite-epoxy components are also finding applications in industrial diagnostic X-ray equipment in parallel with the use of graphite epoxy composites in medical X-ray equipment (96).

2.4.3.13 Musical Instruments and High Fidelity Equipment

Violins and guitars have been designed and built with graphite-epoxy composite soundboards because aged spruce, the traditional construction material, is becoming more difficult to obtain. Laminated graphite/epoxy soundboards have been found to be more reproducible than those made of spruce and to stay better tuned because they do not absorb as much moisture or swell as much as wood. Graphite/epoxy instruments have also been found to give purer tones than wood ones because the damping coefficient of graphite/epoxy exceeds that of spruce at high freqnencies. One such instrument is Ovation's "Glenn Campbell" guitar shich sells for $2500 (19).

The acoustic properties of graphite reinforced plastics are also used to advantage in the pickup arm of the Sony phonograph. The good damping characteristics and high modulus of the arm

minimizes distortions which otherwise would reach the transducer, and the light weight of the arm makes lateral tracking much more precise while minimizing wear of the record grooves.(100)

Graphite fibers are also being used to make shallow loudspeakers of high quality. The speed of sound on the surface of a molded graphite fiber speaker cone is about three times that on the surface of a regular speaker. This results in a more shallow cone which can be placed in inconspicuous cases or which can be fitted in normally inaccessible places such as automobile doors. Such speakers have been made in Japan and are marketed in the U.S. by Poly Audio Inc. of Baltimore, MD.

2.4.3.14 Other Potential Applications

The previous sections list specific applications with advanced composites which were derived from interviews during the course of the program or which were referenced in the published literature that was reviewed. The list is not meant to be all inclusive, and there are understandably other applications of advanced composites in existence which have not been mentioned. However, it is believed that most of the major topics have been covered, and it is also quite likely that applications of advanced composites will expand as the technology diffuses and costs are reduced. In principle, any device currently made with fiberglass reinforced plastics could be made with a hybrid composite and the extent to which this will occur will depend on the associated costs and derived benefits.

3.0 IMPACT ANALYSIS

3.1 INTRODUCTION

In this section, the major areas of human activity which would be likely to be affected by an emerging advanced composites industry are identified and scoped where feasible. In view of the wide variety of applications which could benefit from the use of advanced composites, multifold impacts both of a primary and of a secondary nature can be identified.

The basis of reference for the discussion will be the year 1990 by which time it is projected that consumption of high performance fibers, mainly graphite and aramid, may range from 60 million to 220 million pounds (25,000-100,000 metric tons) per year. At this consumption level, the projected average price of these high performance fibers will be between \$6/lb and \$12/lb. The projected value of high performance fibers sales will be between \$700 million and \$1.3 billion in 1990 (in 1978 dollars), or about \$1 billion/year. In greatest part, these fibers will be combined with fiberglass and incorporated in resin matrix composites. Metal matrix composites will represent only a very small fraction (less than 5%) of the total consumption of high performance fibers. Metal matrix composites will be reinforced principally with alumina and silicon carbide fibers. Metal matrix composites will be principally used in military and aerospace applications. The big unknown with regards to metal matrix composites will be the rate of development and commercialization of short fiber composites, which could be commercially significant by then.

3.2 IMPACT ON DEMAND FOR OTHER STRUCTURAL MATERIALS

The commercialization of high performance fibers will result in relatively little dislocation of other basic materials. Even through the consumption of high performance fibers is expected to increase at a computed average annual rate of 37% to 51%, the consumption of high

performance fibers will be less than 0.1% of the consumption of steel, and less than 1.0% of the consumption of aluminum as shown in Table 3-1. The principal displacement of aluminum will be in aircraft structures which currently represent only about 2% of the demand for aluminum.

Fiber reinforced plastics are currently competing with zinc die castings in many applications. With time, especially in automotive applications, there will be further inroads made on zinc consumption by reinforced plastics. High performance fibers will be a contributing factor, as will be the development of improved manufacturing techniques and new resins.

The development of advanced composites capable of service in a 600^{o}F environment will primarily impact on the uses of titanium in aircraft structures. By 1990, advanced resin composites and aluminum matrix composites will be used in military aircraft structures as replacements for titanium which will curtail its growth.

High performance fibers will act as catalysts for increased consumption of glass fibers and resins in reinforced plastics; it is envisioned that high performance fibers will be mainly used in organic hybrid composites. With a nominal 20% high performance fiber, 40% fiber glass and 40% resin content composite, approximately 10% of projected 1990 fiberglass consumption will be associated with high performance composites. These impacts are within the uncertainties of the projections.

3.3 IMPACT ON RAW MATERIALS SUPPLY

The principal impact of an increased demand for high performance fibers will be on petrochemical supplies. Here again the impact will be small when compared to petrochemicals currently consumed to support the U.S. plastics industry which produced over 13 million tons of plastics in 1976. If the current growth rate of 11% per year is maintained through to 1990, approximately 57 million tons of plastics will be consumed.

TABLE 3-1

U.S. Annual Consumption of Materials of Construction of Interest

Material	Consumption, 10^3 Metric Tons/Yr 1976	1990 Projected	Assumed Annual Growth Rate, %
All High Performance Fibers	0.3	25-90	37-51
Fiberglass	280 [a]	900	9
Polyester Resin, Unsaturated	436 [b]	1300	8
Epoxy Resin	113 [b]	430	10
Reinforced Plastics	700 [b]	2000	8
All Plastics	13234 [b]	57000	11
Aluminum	4521 [c]	11700	7
Steel	116000 [c]	116000	0
Titanium	22.3 [c]	25.6	1
Zinc	841 [c]	605	-2

Source (a) Reference 101

(b) Reference 20

(c) Reference 102

TABLE 3-2

Raw Material Uses of Fossil Fuels
(1975)

	Raw Material Uses (Trillion BTU)	Total Uses (Trillion BTU)	Raw Material Uses as % Total Demand
Petroleum	3119.9	32741.6	9.5
Natural Gas	606.4	19747.9	3.1
Coal	95.1	12683.7	0.7
TOTAL	3821.4	65173.2	5.9

Source: Reference 103

Based on the projected consumption of fibers in hybrids and assuming all the high performance filaments to be graphite made from PAN (with a 3 to 1 weight loss in fiber manufacture), total plastics consumption associated with advanced composites in 1990 would be less than 270 thousand metric tons of PAN and 180 thousand tons of resin matrix material, or a total of 450 thousand metric tons. This is less than 1% of total projected plastics consumption in 1990.

In 1975, all nonfuel uses of fossil fuels represented only 5.9% of total fossil consumption. As shown in Table 3-2, about half of the raw material uses are based on petroleum. A 4.5 x fold expansion of the plastics industry would require about 10% of the 1975 total fossil fuel consumption. In 1975, the petrochemical industry was based mainly on petroleum and natural gas feed stocks. By 1990, it is expected that a significant fraction of petrochemicals will be derived from coal.

The raw material requirements of the advanced composites industry in terms of petrochemical feedstocks will represent less than 0.1% of the total demand for fossil fuels.

3.4 ENERGY ISSUES

Advanced composites and energy issues are closely intertwined. In the nearer term, advanced composites could be a significant energy conservation tool, and in the longer term, they could be essential to the operation of new electrical energy generation and energy storage systems. Advanced composites could also impact exploration and mining of fossil fuels.

3.4.1 Energy Conservation

3.4.1.1 Introduction

The amount of energy needed to move or accelerate an objective is generally proportional to its mass; less energy is

required to operate a low mass dynamic system. Utilization of advanced composites results in energy conservation, simply because the advanced composite system will weigh less than a system made out of another material.

Advanced composites have the potential of significantly reducing transportation energy consumption, and therefore petroleum consumption. Pertinent energy statistics for 1975 are presented in Table 3-3. The transportation sector of the economy consumed nearly one-third of the net national energy production, and over half of the available petroleum. To satisfy petroleum demand nearly one-third of the crude oil supply had to be imported. The distribution of transportation energy in the U.S. in the same year is shown in Figure 3-1. As can be seen from this pie chart, passenger automobiles consumed over half of all transportation energy. Automobiles and trucks combined consumed 71.5% of all transportation energy, essentially all as petroleum fuels. Automobiles and trucks fuel was approximately 40% of the total petroleum consumption.

Air transportation was the next largest consumer of fuel, again principally petroleum fuel. Total civilian air transportation services, including general aviation, consumed 7.0% of U.S. transportation energy which is equivalent to 3.9% of petroleum consumption. Commercial and privately owned automobiles, trucks and airplanes accounted for over 80% of total transportation energy consumption, 83% of the petroleum consumed in transportation, and 46% of all U.S. petroleum consumption.

Energy conservation, especially petroleum energy conservation, is a matter of national concern. The current pressure on the U.S. dollar relative to foreign currencies is in large part due to a negative trade balance, created principally by the need to import foreign

TABLE 3-3

U.S. Energy Consumption (1975)

	U.S. Total	Transportation	Transportation As % of Total
	Trillion BTU	(Million Barrels)	
Total Energy Consumption, Net	56906	18,545	32.6
Petroleum Consumption	32412 (5898)	17,932 (3263)	55.3
Crude Oil Supply	26340 (4541)		
Crude Oil Imports	8690 (1498)		

Source: Reference 103

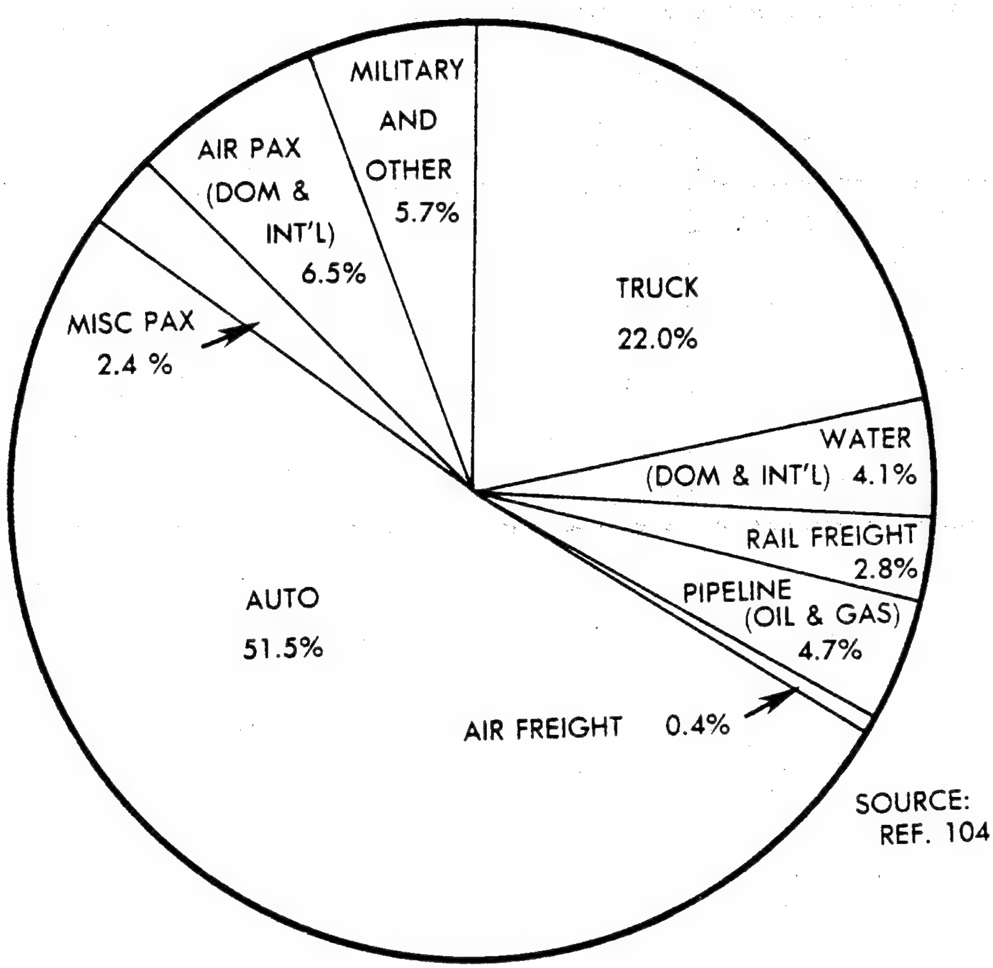

FIGURE 3-1 DISTRIBUTION OF TRANSPORTATION ENERGY IN THE U. S. 1975 (18.545 QUAD)

NOTES:

"MISCELLANEOUS PASSENGER" INCLUDES ALL BUS AND RAIL MODES, PRIVATE BOATING, MOTORCYCLES AND GENERAL AVIATION.

"MILITARY AND OTHER" INCLUDES ONLY THOSE DOD FUEL PURCHASES MADE IN THE U. S. DOD MAKES SUBSTANTIAL PURCHASES FROM FOREIGN REFINERIES. THE VALUE SHOWN IS CALCULATED AS A RESIDUAL BY SUBTRACTING ALL OF THE CIVILIAN MODES FROM THE CONTROL TOTAL FROM REF. 105. THE "OTHER" CATEGORY IS ESSENTIALLY AN ERROR TERM. AT THE TIME OF PUBLICATION OF REF. 105, .278 QUAD OF 1975 PETROLEUM CONSUMPTION WERE UNACCOUNTED.

oil. The rising price of crude oil, concerns about its future availability, and government regulations are all strong motivating forces for energy conservation.

As shown in Table 3-4, extensive use of advanced composites could theoretically reduce petroleum energy consumption by 1.5 quadrillion BTU over a 1985 base line that would already include a significant reduction in automotive fuel consumption as compared to 1975. Approximately 10% of this potential reduction in energy consumption will be obtained by the use of advanced composite structures in 1990. These savings correspond respectively to 4.5% and 0.5% of 1975 petroleum energy consumption.

3.4.1.2 Automotive Energy Conservation

By law, automobiles will become more fuel efficient. As previously discussed in Section 2.4.3.5, new car fleets will have to meet a corporate average fuel economy (CAFE) of 27.5 mpg: this level can be achieved without using advanced composites. By 1985, it is projected that the total fleet fuel economy will be 20.6 mpg (106), which is about 52% more than the 1975 overall fleet average fuel economy of 13.53 mpg (104). The 20.6 mpg economy corresponds to a reduction in crude oil consumption of approximately one billion barrels a year, assuming no changes in automobile use patterns. Because of the changes in automobile design that will occur, the impact of advanced composites on automobile fuel consumption has to be gauged against the performance of a projected state-of-the-art 1985 automobile, and not against current technology.

A measure of the fuel economy to be derived from extensive use of advanced composites in automobile structures is obtained by comparing the fuel economy of a model six passenger automobile, equipped with a given engine and drive train that makes innovative use of aluminum and plastics in its structure to a vehicle with similar performance that makes extensive use of advanced composites in their

TABLE 3-4

Projected Petroleum Energy Conservation Resulting From the Use of Advanced Composites (*)

	Projected Reduction in 1990 Over 1985 Baseline			
	Potential		Probable	
	Trillion BTU/year	Percent Reduction	Trillion BTU/year	Percent Reduction
Automobiles	750	21	50	1½
Trucks, Single Unit	270	21	20	1½
Trucks, Combination	130	10	10	1
Aircraft	150	10	60	3
Other Transportation (not including pipeline)	100	10	10	1
Agricultural Field Machinery	80	20	-	-
Total	1450		150	

(*) Exclusive of Energy Content of Advanced Composite Components

stead. Based on the results of the Report by the Federal Task Force on Motor Vehicles beyond 1980, a six passenger automobile with an innovative weight configuration, but which is otherwise comparable to the current Ford Grenada discussed in Section 2.4.3.5, would have a curb weight of 3200 lbs, about 700 lbs more than the curb weight of the Ford six passenger LightWeight Vehicle that makes extensive use of advanced composites. The fuel economy of the standard Grenada is 17 mpg, the fuel economy of the light vehicle is projected to be 23 mpg, and by interpolation, the fuel economy of the corresponding innovative vehicle is calculated to be 19 mpg. Extensive use of graphite composites results in a fuel efficiency improvement of only 4 mpg, or 21% over an innovative design with current engine and drive train technology, at an assumed emissions level of 0.4/3.4/2.0, as compared to an improvement of 6 mpg, or 35%, over that of a current weight-conscious standard automobile. It is estimated that a vehicle that made extensive use of graphite/glass hybrid composites, but is otherwise comparable to the Ford Light Weight Vehicle, would have a curb weight of 2700 lbs to 2800 lbs, or a test weight of about 3000 lbs, and a fuel economy of 21.4 mpg. With improvements in the drive train and engine configuration, the fuel economy of all these vehicles could be expected to be increased by up to 20% by 1985. The corresponding fuel economies would be 20.4 mpg, 22.8 mpg and 27.6 mpg.

Recapitulating, extensive use of graphite composite in a six-passenger automobile should result in fuel economy improvement of approximately 21% over that attainable with innovative use of standard materials. If a graphite-glass hybrid were used instead, the corresponding fuel economy improvement would be about 13%. It is expected that comparable fuel economy improvement would be attainable in smaller vehicles, as well, if advanced composites were used in the same manner. The implications are that, if advanced composites were extensively used throughout the automobile fleet, the average fuel economy of the fleet would be increased by either 13% or 21% over the 1985 baseline of 27.5 mpg. These numbers correspond to reductions in fuel consumption of the order of 400 gallons and 600 gallons respectively over the current nominal life of an average automobile (100,000 miles over 10 years). If it

is assumed that 600 lbs of hybrid composite or 400 lbs of graphite composite are used in the two model vehicles, petroleum consumption over the life of the vehicle is decreased by about 0.6 gallon per pound of hybrid used to approximately 1.5 gallon per pound of graphite composite used.

The more realistically projected usage of composites is limited to about 20 lbs of hybrid composites in smaller vehicles, and 600 lbs of hybrid composite per vehicle in luxury cars which would comprise 10% of the market. The sales weighted composite usage is about 80 lbs of hybrid per car. Assuming the decrease in fuel consumption projected above, the use of advanced composites should result in a realistic reduction in fuel consumption of about 50 gallons over the lifetime of a car, or about 5 gallons/year. This would correspond to decrease in fuel consumption of about 1.4% for the average automobile.

In discussing trucks, it is useful to distinguish between single unit and combination trucks. In 1975, single unit trucks which comprised 95.3% of the truck population (107) consumed only 69% of the truck energy (104). A significant fraction of these trucks are light duty trucks, that have many of the attributes of automobiles. It is considered that the impact of advanced composites on the fuel economy of the class of trucks will be similar to that of automobiles.

Combination trucks, comprised only 4.7% of the truck population but consumed 31% of the truck energy in 1975. In 1975, the average combination truck was driven 48,662 miles, and consumed 8,448 gallons of fuel, which corresponds to a fuel economy of 5.69 gallons per vehicle mile. Average truck payload was 11.22 tons/vehicle (104). AS discussed in a subsequent section, the payload of a truck is a large fraction of the gross vehicle weight. The use of advanced composites in a truck structure will allow a truck operator to increase vehicle payload while maintaining a constant gross vehicle weight. Conservation of truck fuel would result because fewer vehicle-trips would

be required to haul a given amount of material. Furthermore, there would be additional fuel economy when the trucks travel empty. A limitation on the weight of advanced composites that could be used would be the minimum weight required of an empty truck to resist wind load when on the road.

It is estimated that fuel economies of the order of 10% could be achieved by using 1000 lbs. of hybrid composites in a truck with a GVW of 32,000. Reducing the net vehicle weight by 2000 lbs would result in a payload increase of from 22,000 lbs to 24,000 lbs, or 9%. This would reduce the required number of truck trips by 9%, and would result in an effective fuel economy of 9%, even though the fuel consumption per laden vehicle mile would be invariant. In addition, fuel savings of about 15% would accrue when the truck would be travelling without cargo. It has been reported that non-freight uses of trucks account for 15% of vehicle miles (104). Overall, a 10% reduction in fuel consumption would be expected.

This value represents the potential of advanced composite for reducing truck fuel consumption, but the probable reduction that will occur by 1990 is projected to be less than one-tenth of this value.

A combination truck has a lifetime of 15 to 20 years. If it is assumed that the truck in the above example consumed 8500 gal/year of fuel, the use of 1000 lbs of advanced hybrid composite would result in a reduction in fuel consumption of about 15,000 gallons over the lifetime of the vehicle, corresponding to a fuel savings of 15 gallons per pound of composites used.

3.4.1.3 Aircraft Energy Conservation

Based on data published in Janes, (83), it appears that the characteristics of commercial aircraft in terms of the ratios of empty plane weight, of payload weight, and of fuel weight

to maximum take-off weight are fairly constant. As a first approximation, the empty plane weight is currently approximately 50%, the payload is about 25%, and the fuel is about 25% of the maximum takeoff weight. Another way of expressing the fuel weight is to consider its weight equal to one-third the combined weight of the empty plane and payload. The fuel economy of an airplane is also proportional to its maximum takeoff weight.

It has been reported that extensive use of advanced composite structures in transport aircraft would result in a reduction in the structural weight of an aircraft of 26% (108). Assuming that the structural weight is 60% of the empty takeoff weight, this corresponds to an empty weight reduction of 15%. If the resulting aircraft were to be operated at constant payload, the takeoff weight of the advanced composite aircraft would be 89% of the all metal aircraft, and a fuel economy of 10% would be obtained. Conversely, it would be possible to increase the pay load by 31% without increasing the aircraft takeoff weight or changing the fuel economy per vehicle distance travelled. However, fuel consumption per ton-mile or per seat mile would be decreased by 24%.

It is unlikely that there will be extensive use of advanced composites in primary structures of commercial aircraft in 1990. However, it is not unreasonable to consider that extensive use of advanced composites will be made in secondary structures which could represent 10% of the structural weight of the airplane and would result in an overall 3% weight reduction in the empty weight of the aircraft. Using the same methodology as above, in this case, fuel consumption at constant payload would be reduced by 2%, or payload could be increased by 16% at constant fuel consumption.

The same general argument would hold for general aviation aircraft. In fact, the fuel economy savings calculated above for extensive use of composites are close to those predicted for the Lear Fan. It is difficult to predict how successful this airplane will

be and how widely advanced composite structures will be used by competitors but by 1990, it is expected that advanced composites will result in about a 2% reduction in fuel consumption for general aircraft, but this decrease represents only a 0.002% reduction in overall transportation energy.

The greatest proportional increase in fuel economy will occur with military aircraft which by 1990 will have structures containing anywhere from 15% to 65% advanced composites. Corresponding fuel savings could range from 5% up to 30% (59). However, on a national basis, the resulting savings would be small.

3.4.1.4 Other Equipment

The savings that would accrue from the use of advanced composites in other forms of transportation were not analyzed, but the improvements for buses and light rail equipment, for example, should be similar to those achieved with trucks. Advanced composites should result in decreased fuel consumption in small boats, most probably comparable on a proportionate basis to the savings obtainable in automobiles. Advanced composites should not have much impact on fuel efficiency of large marine transports nor on railroad freight travel since in those instances, the net weight of the vehicle is a relatively small fraction of the total gross weight, as subsequently discussed.

Advanced composites could potentially impact fuel consumption by agricultural field machinery which consumed 391 trillion BTU in 1974 (109). Assuming that this number is also valid for 1975, it is equivalent to 0.7% of national energy demand or 2.1% of transportation energy demand in that year. It is doubtful that advanced composites will have had much impact on energy consumed by agricultural field machinery by 1990. However in the longer term, there may be a potential reduction of the order of 10-20%.

3.4.1.5 Manufacturing Energy Conservation

In assessing energy conservation it is also necessary to take into account the energy needed to manufacture a component out of a given material. The energy contents of a unit volume of various engineering materials are given in Table 3-5. The energy contents of the advanced composites were estimated as follows:

Aramid-Resin: The energy content of aramid was assumed to be equal to the energy content of nylon. The energy content of the composite was obtained by adding energy contents of Aramid and polyester and dividing by two.

Graphite-Resin: The energy content of graphite was assumed to be equal to three times the energy content of an acrylic resin times the density ratio of graphite to acrylic resin, plus 10% for heating. The calculated energy content of graphite is 16,000 BTU/in^3. The energy content of graphite resin composite is obtained by adding this value to the energy content of polyester and dividing by two.

Boron-Resin: The energy content of a cubic inch of boron was obtained by adding the heat of formation of a pound mole of boron trichloride to the electricity required to reduce a pound mole of boron, dividing by the molecular weight of boron and multiplying its density. The energy content of boron is estimated about 34,000 BTU/in^3. The energy content of a pound of boron-resin composite is obtained by adding the energy content of polyester and of boron and dividing by two.

On a unit volume basis, FRP has a lower energy content than any of the other products listed. Graphite composites are estimated to have an energy content intermediate to that of steel and aluminum, while the energy content of a boron composite is much higher than any of the other materials listed. Aramid composites and 20% graphite/glass hybrid composites (not shown) are estimated to have an energy content comparable to that of organic polymers, and which is about half of the energy content of steel on a unit volume basis. Overall, no

TABLE 3-5

Specific Energy Content of Structural Materials

Material	Specific Energy Content BTU/lb	Specific Energy Content BTU/in^3	Source
Metals			
Steel	28,000	8,100	Ref. 110
Aluminum	108,300	10,830	Ref. 110
Plastics			
Polyester Resin		3,500	Ref. 110
Acrylic Resin		3,300	Ref. 110
Nylon Resin		4,200	Ref. 110
Composites			
FRP(*)	40,100	2,900	Ref. 110
Aramid-Polyester		4,000	Estimate
Graphite-Polyester		9,500	Estimate
Boron-Polyester		18,000	Estimate

(*) Fiberglass Reinforced Plastics

significant manufacturing energy impact is envisioned by replacing metals with advanced composites on an equal volume basis.

3.4.2 Other Energy Impacts

In the longer term, advanced composites could be essential to the operation of a variety of advanced energy systems, which include energy storage systems such as flywheels and lead acid batteries, either for electric vehicle use or utility load leveling applications. Advanced composites would also be used to construct platforms for orbital solar energy collection devices now being proposed. Advanced composites would be needed in a variety of advanced electric power generation systems, for example in alloys for industrial turbines that could operate at temperatures in excess of 2000°F (1000°C), copper matrix composites for contacts for proposed homopolar generators, or advanced composite reinforcement for magnetic fusion generators. Another potential use of advanced composites that could impact electrical energy production on a much nearer term would be the more prosaic use of lead-matrix graphite composites for electrical generator support bearings. Such bearings would be less likely to be damaged during an emergency or accident than the babbitt bearings now used which have to be oil cooled. It is to be noted that the shutdown of the cooling oil circulation pumps of Consolidated Edison Company of New York's "Big Alice" generator during the Northeast Power failure of November 1965 resulted in the failure of main generator bearings, which in turn, resulted in the shutdown of that generator for a number of months.

As mentioned in Section 2.4.3.9, advanced composite abrasive tools could shorten the time required to drill an oil well. This could reduce the cost of oil exploration and production, and the long term effect would be increased oil production.

3.5 TRANSPORTATION

3.5.1 Introduction

Advanced composites can have a major impact on transportation systems in that they can increase the ratio of payload to gross vehicle weight as well as increase vehicle fuel economy as discussed in Section 3.4. Typical values of the current ratio of payload to gross vehicle weight for different types of transportation equipment are presented in Table 3-6. The impact of a 10% decrease in vehicle tare weight was obtained by adding this decrease of vehicle weight to the payload and assuming that gross vehicle weight, fuel capacity, and thus range would remain unchanged.

As can be seen from this table, a 10% tare weight change has a much greater impact on the payload of an airplane than that of a railroad freight car, which points out that weight saving has more value for aircraft than for railroad cars, and therefore that advanced composites will be more valuable in aircraft applications. The introduction of significant quantities of composites in transportation equipment would have a series of secondary impacts which will vary with the sector, as presented below.

3.5.2 General Aviation

Advanced composites would have a very significant impact on light aircraft, and the major impacts would be that light aircraft would be smaller, more productive, and less expensive to operate. The major impacts would be on business aircraft, which could be made significantly more fuel efficient. The introduction of light fuel efficient advanced composite aircraft could result in a significantly greater demand for private air transportation, and a commensurate increase in aircraft sales as well as supporting services, in terms of airports, fuel services, maintenance support services, and personal service industries that would depend on travel such as hotels, restaurants, and automobile rentals.

3.5.3 Commercial Aviation

Advanced composites could have a major impact on the

TABLE 3-6

Impact Of Change in Vehicle Tare Weight on Payload

Vehicle	Payload/GVW Current Technology	Payload/GVW with a 10% Tare Weight Decrease	Percent Increase in Payload due to Change in Tare Weight
General Aviation			
Turbofan/Turbojet Aircraft	0.08-0.14	0.13-0.20	40-60
Turboprop Aircraft	0.14-0.23	0.20-0.28	24-40
Reciprocating Engine Aircraft	0.26-0.28	0.32-0.35	23-25
Helicopters, Civilian	0.24-0.26	0.29-0.31	19-21
Transportation Aircraft			
Short haul (DC 9, B-737)	0.23	0.28	22
Long haul (DC 10, B-747)	0.18-0.23	0.23-0.28	21-26
Automobile			
4 passenger	0.32	0.39	18
6 passenger	0.29	0.36	24
Class VIII Truck (73,500 lb GVW)			
Dense Freight	0.64	0.68	6
Bulky Freight	0.54	0.59	9
Railroad Freight Cars			
General Purpose	0.60	0.64	7
Tank wagon	0.65	0.69	5
Hopper Car	0.66-0.73	0.69-0.79	4-5
Hopper Car (Al sides)	0.78	0.80	3
Merchant Ships			
Passenger	0.50	0.55	10
Cargo	0.69	0.72	4
Tanker	0.71	0.76	4
Intermodal Containers (Land/Sea)			
Dry General Cargo	0.90	0.91	1
Tank	0.83	0.85	2
Refrigerated	0.84	0.86	2

operation of commercial airlines. Extensive use of advanced composites would result in either decreased fuel consumption, as previously discussed, or increased payload (i.e. more passengers per aircraft). In view of the fact that a given percentage in aircraft weight results in a much larger proportionate increase in payload than in fuel economy, the airline would find it more profitable to increase the payload of the aircraft of a given configuration. For a given traffic volume fewer flights would be required which would impact flight schedules, airline employment purchases of operating supplies, as well as the purchase of transport aircraft in the first place. The requirement for flight crew personnel which are proportional to the number of flights would decrease, but the requirements for cabin attendants and ticket agents which are proportional to passenger traffic would remain the same. The requirements for maintenance personnel could either increase or decrease depending on the relative maintenance needs of metal and composite aircraft. Fuel purchases would be significantly decreased, as would purchases proportional to the number of planes in service, such as tires, for example. The number of aircraft required by an airline would be decreased and fewer flights would be needed to perform the same service.

The above discussion neglects any effects of the price of an airplane ticket or of frequency of scheduling on the demand for air transportation, or the regulatory requirements for maintaining minimum service. Assuming that the acquisition and operating costs of an advanced composite aircraft were approximately the same as that of a metal aircraft, it would be possible for an airline to decrease the price of a ticket proportionally to the increase in payload, which could result in increased route traffic, and increase demand for airline service.

This discussion assumes that the configuration of the aircraft would be similar to those in current service, but this may not necessarily be the case. Options open to the airlines would be to specify new smaller aircraft that would retain current payload characteristics, but would be less expensive to operate. The major impact of such a decision would be on the cost of an airline ticket and airline profits and would not otherwise significantly affect overall airline operations,

except to the extent that traffic volume increased as a result.

The other potential impact of advanced composites would be that they would allow the airframe manufacturers to build an aircraft that could be substantially larger than any metal aircraft now in commercial service. It would be interesting to determine the limiting size that an aircraft could attain with existing engine technology, by extensively using advanced composites, and then determine the potential consequential impacts in terms of required traffic volume, and airport requirements such as runway dimensions and load bearing capacity.

The same impact arguments apply to air freight. In this instance, the major impact would be to make the cost of air shipment less expensive and make it more competitive with other forms of rapid freight transportation.

3.5.4 Automotive Transportation - Passenger Auto and Light Trucks

The potential direct impacts of advanced composites on automobiles has been discussed in Section 2.4.3.5. The change in vehicle payload ratio will have little direct impact other than on fuel economy to be derived. The use of advanced composite structure will be an extension of the increased use of fiberglass reinforced plastics in automobiles and will be an evolutionary change.

The combined effects of decreased vehicle weight and changing materials of construction will also have an effect on the performance, handling, crashworthiness and damageability of an automobile. The impact of these changes on vehicle safety and damageability is an open issue; however, it is presumed that when these materials are introduced into service, the resulting vehicles will be at least as safe as the metal vehicles they are replacing.

The extensive use of fiberglass reinforced plastics and

of advanced composites may alter slightly the skills needed to repair and maintain an automobile. Reinforced plastics and plastic putty are currently used to repair visual damage to an automotive structure, and thus it will probably be possible to apply the same compounds in the same manner, and for the same purpose,to advanced composite plastic structures. Repair of extensively damaged structural members would require training of body shop operators and garage mechanics and could require some specialized facilities, such as curing ovens and tooling, but given the advances of elastomeric tooling, and the current practice of curing paint and putties by the application of heat, this may not be a major problem.

The trend towards lightweight vehicles will result in the use of more corrosion resistant materials in its construction. Regulatory demands on the automotive industry have had a tendency to increase the consumer's acquisition cost. These factors will result in an increase in the average length of ownership of a new car. There has already been an increase in the maturity of the average new car loans. Prior to 1974, very few new car loans had a maturity of more than 36 months (111). The percentage of long term new car loans has increased rapidly since then. In 1976, over 30% of new cars had a maturity of more than 36 months, and it is estimated that currently 50% of new car loans have a maturity of more than 36 months. If this trend continues, financing periods of five or more years may become common in the future. Increased length of ownership of a new car will also result in decreased annual sales since the new car buyer will postpone time of purchase,which may require automotive companies to develop new marketing tools to maintain healthy operations.

These changes will occur whether or not advanced composites are used in automobiles. At best the use of advanced composites in automotive structures may reinforce the trend, but these materials will not be the causative factor.

3.5.5 Automotive Transportation - Heavy Trucks

The impact of advanced composites on heavy trucks would be to increase the hauling capacity of a truck of a given gross vehicle weight, and increase its fuel economy. However, unless there is extensive substitution of advanced composites in truck structures, the general impact on the trucking industry will be small because the ratio of payload to gross vehicle weight is of the order of 0.60. Utilization of advanced composites which result in a 10% weight reduction of a combination truck will result in no major secondary impacts on truck scheduling, employment, etc.

3.5.6 Other Transportation Systems

The use of advanced composites would marginally improve the hauling characteristics of railroad cars, merchant ships, and even intermodal containers, for which a small decrease in tare weight only results in a small increase in payload. The use of advanced composites might allow a railroad car to be marginally more productive. This does not imply that advance composites would not be used in these applications if the economics were favorable, but simply that few secondary effects would result.

3.6 AGRICULTURE

The manufacture of larger agricultural equipment with advanced composite structures as discussed in Section 2.4.3.6, could result in some major impacts. For example, the use of this equipment could result in higher production, especially of large acreage crops such as grains and soybeans, and therefore the optimum size of a farm could be impacted. It would tend to make farming more capital intensive than it currently is while tending to reduce direct operating costs per acre such as fuel and labor costs. A significant increase in production would have secondary impacts in terms of the price of these crops and ultimately food, commercial storage and transportation facilities, and the U.S. balance of trade.

The extent to which these changes would occur would be strongly influenced by the agricultural policy of the government, and the nature of incentives given to the farmer to increase or decrease production.

3.7 MILITARY PROGRAMS

Advanced composites have well identified applications in military programs which have been reviewed in Section 2.3. The secondary impacts of these activities on the civilian sector of the economy are primarily employment in the aerospace industry and the development of a technology base that can then be utilized in other areas. Current interest in commercial applications of advanced composites would not even exist had there not been prior development of the technology by the military. Ready availability of the data base and information gathered on advanced composite technology in support of military programs to the aerospace industry has been a catalyst to the commercial development of the technology.

Many aerospace companies are involved in non-military uses of advanced composites, capitalizing on their experience and easy access to documentation. A common complaint by a number of commercial firms that have not participated in defense contracts, has been accessibility and availability of technical reports and other data sources published by the military services. This is especially true of reference documents such as design and fabrication guides which officially have an unrestricted circulation, but which are, however, practically very difficult to obtain outside the defense community.

Another impact of military requirements for advanced composites on the civilian sector is the capital investment in manufacturing facilities needed to fabricate advanced composite structures for military systems. Extensive use of advanced composite structures in military aircraft, in particular, would require a significant capital investment on the part of the contractors in new manufacturing facilities. This

results in a bias against the use of advanced composites as compared to metal structures since much of the metal fabrication equipment in the manufacturing facilities of the major prime contractors is government furnished equipment. The imbalance in the nature of the manufacturing facilities has implications in terms of military preparedness of the U.S. aerospace industry.

3.8 SPACE PROGRAMS

In general, the impact of current space programs on the civilian sector of the economy is similar to that of military programs, with one exception. The size, power and transmission qualities of orbiting communications and information gathering satellites are in no small measure due to the properties of the high modulus graphite-epoxy composites used in their structure. It would be interesting to assess the marginal amount of the advanced composites on the cost and amount of information being transmitted by orbiting satellite systems.

In the longer term, the projected use of advanced composite materials as the material of construction for large space structures makes it possible to argue that the industrialization and colonization of space are secondary impacts of advanced composite technology. The potential impacts of this occurrence would alter significantly our current perception of life as proponents of this endeavor have already clearly indicated (112).

3.9 LEISURE ACTIVITIES

Advanced composites are used currently in a wide variety of leisure products. These include top of the line sports equipment, small craft, musical instruments and high fidelity sound reporduction components, and the use of advanced composites in these markets will expand as the price of the high performance fibers decreases.

Personal travel is a major leisure activity. The impact that

advanced composites will have on the first cost and the cost of ownership of privately owned automobiles, trucks (i.e. recreational vehicles or camper), or light airplanes, or on the cost of using public transportation will directly influence recreational travel in the U.S. If there is a dramatic rise in petroleum fuel costs, or a drop in its availability, personal travel and tourism would be inhibited. To the extent that advanced composites decrease the amount of fuel, and the cost of traveling from one place to another, these materials can be considered to reinforce this activity .

Secondary impacts that would result from restricting leisure travel would be decreased revenue for industries and regions that are related to tourism, e.g. public carriers, hotels, campgrounds, restaurants, service stations and gift shops in resorts and areas far from urban centers. Concurrently, those facilities and establishments near urban centers could benefit from travel restrictions.

To the extent that communications are interwoven into leisure activities, the use of advanced composites in communications satellites and in radio and television receiving equipment has an additional impact in this sphere.

3.10 HEALTH ISSUES

Advanced composites will have a variety of impacts that relate to human health. the beneficial aspects will result from the increasing use of advanced composites in medical instrumentation and devices. As graphite reinforced X-ray equipment becomes more common, average exposure of the public to standard diagnostic X-rays will decrease. The correlation between X-ray exposure and the incidence of cancerous growths is well established, (113, 114) so that a secondary impact of advanced composites will be a decrease in diagnostic X-ray induced carcinoma. Computed Tomography (CT) is a new technique in general diagnostic X-ray with which soft tissues and organs not normally visible can be inspected radiographically. Because of the degree of contrast required and

relatively small variations in X-ray absorption of body tissues, minimal X-ray absorption and a concurrent high degree of rigidity are needed of the patient support structures. These requirements are both met with graphite-epoxy composites to a degree not attainable with other materials. The full benefits to be derived from CT body scanning are not yet known as the method is still experimental, but however it is expected that this method will be rapidly become accepted as a specialized diagnostic tool, much in the manner that CT brain scanning has become the diagnostic method of choice for examination of possible brain lesions.

The potential benefits to be gained from implanted advanced composite prostheses are enormous. Dental surgeons have for decades sought a material for an artificial tooth root implanted through the gingiva into the jaw bone, to provide support for a tooth bridge or complete denture. Total joint replacement such as hip arthoplasty could be another important application. According to Jenkins and Carvalho, approximately 30,000 such operations were carried out in the UK alone in 1973 (28). On prorated population basis, one would estimate that over 100,000 such operations are performed in the U.S. each year. The less exotic use of advanced composites for external prostheses and medical supports should develop rapidly as the materials become less expensive. This use will result in the qualitative benefits of increased comfort and mobility to the lame and handicapped.

The filamentary structure of high performance fibers presents the major potential hazard to human health of advanced composites. Current NIOSH criteria for a recommended standard for occupational exposure to fibrous glass (115) distinguish between fibers that are larger than 3.5 μm in diameter, and those that are smaller than 3.5 μm in diameter. "The primary health affects associated with the larger diameter fibers involve skin, eye and upper respiratory tract irritation, a relatively low incidence of fibrotic (lung) changes and preliminary indications of a slight excess mortality risk due to nonmalignant respiratory diseases. In this regard, NIOSH considers the hazard potential of fibrous glass to be greater than that of nuisance dust but less than that of coal dust or

quartz. With small diameter fibers, much less information on health is available...On the basis of currently available information, NIOSH does not consider fibrous glass, with a diameter of less than 3.5 μm, to be a substance that produces cancers as a result of occupational exposure. However, the smaller fibers can penetrate more deeply in the lungs than larger fibers, and until more definitive information is available, the possibility of potential hazardous effects warrant special consideration. The recommended environmental levels are based on evidence in those instances where exposure to asbestos and fibrous glass can be compared, and considering the limitations and deficiencies of such data, fibrous glass seems to be considerably less hazardous than asbestos. In addition,"......"NIOSH considers that until more information is available, the recommended standard can also be applied to other man-made mineral fibers."

The last sentence is applicable to the fibers of interest to the study. Currently, all the high performance fibers are manufactured with diameters larger than 8 μm and fall within the large diameter fiber category. As such, they should have little health impact other than as an external irritant and nuisance dust. A concern is that fibers smaller than 3.5 μm in diameter may be subsequently formed. Filaments could break or splinter while the fibers are handled and processed into composites, or if composite components are machined. Small fibers could potentially also be released by a burning composite structure. Filament diameters may also be made in the future as methods for handling gossamer threads are improved, especially if these filaments were to have improved mechanical properties. It is noted that the SiC whiskers made by EXXON Enterprises, Inc. from rice hulls contain a large fraction of particles in the sub 3.5 μm size range.

A general potential hazard to the health of the population derives from the flammability of all reinforced plastics, and the generation of toxic gases when these burn, as discussed in Section 3.12.3.

There are also a number of potential health hazards to the work

force associated with the manufacture of certain fibers, resins, or composite structures. Health hazards related to fiber manufacture were noted in the various parts of Section 2. The major problem here may be the exposure to carcinogens that would occur with the manufacture of pitch based graphite. The hazards associated with handling of resins and fabrication of resin based composites would be the same as those presented by the fabrication of reinforced plastics.

3.11 ENVIRONMENTAL IMPACTS

3.11.1 Air Quality

There will be little direct impact on air quality from the manufacture and use of advanced composites.

The impacts of fiber manufacture are discussed in Section 2.2. There will be a corresponding impact associated with manufacture of the various matrices, and which will depend on the matrix being considered. Solvent losses from prepreg manufacture will have a minor impact. The fabrication of advanced organic composites will present the same impacts as those of fiberglass reinforced plastics, where the main concerns are the presence of organic vapors in the work place, such as styrene monomer emissions from handling of unsaturated polyester sheet molding compound.

In use,advanced composites will have indirect beneficial impacts on air quality. A secondary impact of the use of advanced composites in transportation equipment will be a reduction in mobile source pollution. As a first order of approximation, the less fuel used, the smaller the amount of combustion products generated, and for a given level of emission control technology, the lower the amount of pollutants emitted. Another secondary impact will be the structure of emissions from chemical process plants through the use of advanced composites in the construction of scrubbing towers and other process plant air quality control equipment.

3.11.2 Water Quality

There will be negligible impact on water quality from the manufacture and use of advanced composites. There is no direct use of water in the manufacture of any of the fibers identified, with the possible exception of alumina FP, where water is used to slurry alumina particles in the manufacturing process, in a manner which lends itself to total recycle. There will only be minor effluents from scrubbing towers used to remove vapor contaminants formed in the fiber manufacturing process. The impact of matrix manufacture will depend on the matrix. There is little water needed for prepreg or component manufacture other than for indirect cooling purposes.

The only impact that can be identified from the use of composites is a positive impact associated with the construction of water pollution control equipment from advanced composites.

3.11.3 Solid Waste

The disposal of advanced composites is going to be difficult. In general, any composite, by its very nature, is more difficult to reclaim and recycle than its constituting components. It is expected that most of the advanced composites produced will have thermosetting resin matrices. At the moment, there is no effective way of recycling thermosetting resins, and the only current means of disposal is land fill. Recyclability is a potential problem that may arise with the production of a light weight automobile. A vehicle that would contain a large concentration of aluminum and other light metals that could be effectively recycled would be of value to scrap processors. A vehicle that contained many individual parts that could be easily removed would be of value to autowreckers and the used automotive parts industry. Integrated parts and structures made of advanced composites, on the other hand, would be difficult to recycle, as would a vehicle that made extensive use of advanced composites. Problems with the disposal of reinforced thermosetting resins would be similar to the current problem of

disposing of used tires.

In order to prevent an accumulation of junk automobiles that would greatly exceed the problem of the mid-sixties (116), the technology of recycling thermoset organic compounds has to be improved, or legal provisions, such as those being suggested in the Solid Waste Act of 1976, would have to be instituted.

Advanced composites, especially short fiber composites made with thermoplastic resins could potentially be recycled because the matrix can be softened and reshaped. Primary scrap generated in the manufacture of advanced composites would generally be recycled as part of the fabrication process. The recycling of post-consumer scrap of this kind will depend on the amount, concentration and value of the material. Currently, there is no reclamation of any post-consumer plastic scrap.

The recycling of metal matrix composites will be analogous to the recycling of specialty, alloys which are normally recycled because of their high unit value.

3.11.4 Noise

The use of advanced composites could significantly reduce industrial and environmental noise. First, the fabrication processes used to make advanced composites, particularly organic matrix composites, are less noisy than common fabrication processes used to make metal parts, such as forging and stamping. Secondly, the use of parts made of advanced composites in high speed machinery has resulted in noise reduction as a result of the high modulus and damping characteristics of advanced composites. Manufacture of items such as gears, gear housings, and high speed moving parts out of advanced composites could result in a major reduction in factory noise level. Secondary effects that would accrue would be a lower industrial accident rate, less impairment of hearing of factory workers and a generally more comfortable work environment.

3.11.5 Electrical Interference

A potential problem associated with certain classes of advanced composites, specifically organic matrix composites that contain graphite fibers, is the accidental release of conductive fibers into the atmosphere and the subsequent interference with electrical circuits and equipment. Uncontained graphite filaments, especially fragments of individual small diameter fibers, can become easily airborne and be transported by air currents over a relatively wide area. Because of their conductivity, graphite fibers which settle on/or across electrical contacts or circuits can cause resistive loading, temporary shorts, or electrical arcing which could damage electrical equipment or result in its malfunction (117).

In the past, there have been malfunctions of electrical and electronic equipment, and in some cases, fires, in industrial plants producing or using free fibers. The accidental disposal of large quantities of long, free fiber in an incinerator not equipped with any emission control systems did result in the atmospheric release of a high concentration of long graphite fibers. Some of these long fibers landed across the poles of a main transformer of a local power station, causing a temporary power failure in the locality involved. As discussed in Section 2.2, these problems have been brought under control in graphite manufacturing facilities by the institution of protective measures and procedures.

The uncontrolled release of graphite fibers or lint from burning graphite-organic matrix composites is a problem of current concern. Graphite fibers are less flammable than organic matrices, such as an epoxy resin. The matrix can be preferentially consumed in a burning composite, resulting in the formation of an uncontained graphite fiber skeleton, from which fibers can break off and diffuse. This diffusion problem can be compounded if the fire is accompanied by an explosion.

With the emerging interest in the use of organic graphite

composites in non-military applications, an interagency task force, under the technical leadership of NASA, has been established to examine the ramifications of this problem. Until recently the topic was classified, and much of the test data obtained by the military agencies is not, as of yet (3/78), available to the public.

In the near term, this problem is of concern to the advanced composites community because of the predominant use of graphite in applications where stiffness and strength are both desired. There are no other fibers currently available that could be cost effective substitutes. The concern is further compounded by a decision on the part of the NASA to postpone funding the flight phase of new wing applications of graphite composite structures until the problem is better defined.

In the longer term, the risk of introducing graphite composites into commerce must be assessed in terms of both the potential benefits to be derived from their use and the costs of unscheduled interruptions of electrical service and the resulting consequential events. The benefits to be derived from the use of graphite composites are easier to assess than the risks and potential costs. At the moment, there are insufficient data to arrive at any valid conclusion, and it is possible only to speculate as to the severity of the problem. Answers are required to questions such as:

a) Are the problems associated with the diffusion of graphite filaments in the atmosphere significantly different than those that have been encountered in the past with the atmospheric diffusion of other forms of conductive carbon particles, such as soot or carbon black, that can form filamentary agglomerates? Is there a fiber release problem associated with hybrid composites, especially fiber glass hybrids (where fusing of the glass could result in a coherent mass)?

b) What is the probability that a fiber release event will occur?

What is the potential number and severity of these events (in terms of fiber release) as a function of type and intensity of use of graphite composites?

c) How would released fibers diffuse in the atmosphere? How long and how far would these fibers be carried aloft as a function of atmospheric conditions? Could deposited fibers be dispersed and carried along further?

d) What equipment would be subject to malfunction in the case of graphite fiber deposition? What deposition conditions would result in malfunction? What is the probability that such a deposition could occur? What would be the consequential events from a malfunction and the potential damages that could accrue? What provisions could be taken to prevent fiber deposition? What would be the costs of these safeguards?

It is expected that the interagency task force that has been assembled will provide the necessary information to form the basis of a rational policy towards the future use of graphite composites.

3.12 PRODUCT SAFETY AND RELIABILITY

3.12.1 Product Reliability Issues

An important consideration in the use of new materials in structural applications is the ability to provide a long trouble free life under the expected loading and environmental conditions. The user must be assured that the ultimate strength, load limit, fatigue characteristics and residual strength of these materials during the operational life of the structure are defined and well understood. A new structural technology must not contain any reliability or maintenance surprises. Unpredicted failures are known as accidents, and can result in economic losses, property damage, human injury and/or loss of life.

A significant fraction of past and current efforts of

advanced composite technology has been devoted to obtaining a better understanding of the basic materials properties, to the development of test methods, to acquiring a statistically significant experimental data base for the establishment of safe and reasonable material allowables, to determining the effects of long term environmental exposure on the properties of advanced composite materials in use, and to the development of accurate design procedures and methods of structural analysis that take into consideration the non-isotropic properties of advanced composites.

The historic evolvement of advanced composite technology has been characterized by a significant amount of conservatism and restraint on the part of potential users. With few exceptions, extensive testing and analysis has been performed before incorporation of an advanced composite structure in any aerospace operational system. Initial uses of advanced composites were limited to small parts not critical to the safety or operation of the structural system. Advanced composite structures were then designed and utilized on a substitution basis as one to one replacements for metal structures, and which remained available as back up systems. Structures that make extensive use of advanced composites are only now, after over fifteen years of experience, being considered seriously. During this evaluation there has been an extensive amount of continued testing, quality control and field evaluation. For example, the graphite-epoxy components of the Triton C-4 missile are radiographed numerous times during the course of their manufacture. Acceptance criteria are rigid throughout the production cycle. Materials, methods and procedures are closely scrutinized before they become qualified.

This philosophy has resulted in a slow and steady evolution and expansion of advanced composite technology, marred by relatively few accidents and surprises (such as, for example, the attack of polysulfone graphite composite spoilers by aircraft hydraulic fluids). The demands of this philosophy are patience and a large budget. An additional impact of this philosophy is that it has constrained the development and introduction of new technology. The certification cycle required to qualify a raw material or manufacturing process tends to promote continued

use of a previously certified material and process in new applications rather than using new or modified materials and methods that could be functionally more effective. The process is self reinforcing in that as more and more experience is gained with a given material and manufacturing method, the greater the level of confidence in that material and/or method, and the more likely it will be respecified.

New product development has been limited to those materials that offer a major potential improvement in performance or cost reduction for established markets (e.g. polyimide matrix composites for military aircraft) or entry in new markets (e.g. unsaturated polyester matrix composites for automotive application).

Entry of advanced composites in new fields of application has been cautious as well, especially in that advanced composites are usually considered for use in highly stressed parts that are subjected to repetitive loads. A critical factor in the decision to use advanced composites instead of metals in a new application is the degree of confidence that the manufacturer has that the advanced composites will perform as expected. Competitive pressures often dictate that a new product be placed on the market within narrow constraints of price and time. Many potential applications of advanced composites can not support extensive product development programs either in terms of costs or lead times, and in many instances, if sufficient design data and use experience are not readily available to the manufacturer, advanced composites will not be used even though potential benefits could accrue.

The major risks associated with the expanded use of advanced composites will be due to unforeseen degradation or environmental interaction of the advanced composite structure, the willingness of a manufacturer to gamble on the structural integrity of a product in a new application, and/or human error.

Unforeseen factors represent the major risk in the use of advanced composites, with the greatest unknown being their long

term behavior and properties. There are a very few advanced composite structures that have been in service for ten years or more. The validity of transposing data obtained under one set of use conditions to another is also an issue. This risk can be minimized by the development and application of improved non-destructive testing (NDT) technique that could be applied in the field as part of a scheduled maintenance cycle.

The proliferation of product liability lawsuits in the past few years has made manufacturers very conservative in their introduction of new product technology. Since the total experience factor for advanced composites is significantly lower than for metals, a manufacturer already undertakes a higher perceived risk in simply using advanced composites instead of a more established material. As a result, a manufacturer will tend to be more conservative in his use of advanced composites than in the comparable use of metals.

Human error is a factor that cannot be eliminated. An advanced composite structure could be improperly designed, manufactured, used or monitored, but so can metal or wood structures. The major difference between advanced composites and the more common materials of construction, is that there are no generally accepted use codes for advanced composites, while universal specifications and standards exist for steel, for example. In the aerospace industry, these specifications vary with each of the major manufacturers, and moreover the requirements and specifications for advanced composites established by government agencies vary with the agency, or with the application. There is a need for common design standards and product specifications that would be greatly accepted as measures of good engineering practice.

3.12.2 Crashworthiness

The previous section considered the structural reliability and integrity of advanced composites within their design specifications. Another issue is the behavior of advanced composites when subjected to a high impact load as would occur in an automobile accident.

Advanced composites, especially resin matrix composite are inherently brittle materials that do not deform plastically, whereas metals exhibit plastic deformation. The crashworthiness of current transportation vehicle is based on energy absorption by deformation of the metal structure. There are some questions as to the crashworthiness of advanced composite structures. If improperly designed, an advanced composite structure could shatter and fracture into sharp shards that would be an additional post-crash hazard to persons in or near the accidental vehicles. However, there is also evidence to indicate that advanced composite structures can be designed to fail safely, and that crash energy can be absorbed by delamination of the composite or by fiber pull out. It has also been suggested that fiber composite structures would absorb a greater load elastically than a metal structure, so that low velocity impact damage would be less severe for an advanced composite structure than for a metal structure.

3.12.3 Flammability

Regulatory agencies and insurance companies are becoming increasingly concerned with the fire hazards of reinforced plastics, which can act as additional fuel and result in the generation of smoke, soot, and toxic gases. The flammability of advanced composites is not significantly different than the flammability of fiberglass reinforced plastics since flammability is a matrix dependent characteristic. The degree of fire hazard will depend on the specific composition of the matrix rather than on the nature of the reinforcing fibers. The consequential impacts of the flammability of advanced composites will be the same as those of fiberglass reinforced plastics which are well recognized, except that graphite composites present an additional potential hazard to electrical equipment as discussed in Section 3.5.5.

3.12.4 Lightning Strike Damage

The low conductivity of organic matrix composites make lightning strikes of advanced composite skin structures a potential hazard to a structure. Unless provisions are taken to diffuse the electrical

energy of a strike, it will be concentrated in the advanced composite which can heat up, and catch fire and even explode. This problem has been overcome by providing an electrically conductive path on the airplane skin. One approach has been to use aluminum leading edge in front of, and a 5 mil thick anodized aluminum film over the surface of an advanced composite skin structure (118). There are a number of other approaches which include positioning of metal bleeder rods and conductive joint design, which indicate that lightning strike of a composite structure is a technically solvable problem.

3.12.5 Reliability of Repaired Parts

The military services have been gathering service experience on advanced composite structures over the past ten years (119). Repair techniques for structural restoration of resin matrix composite aircraft structures with large area damage have been developed and experimentally validated (110). These methods have been used in the field, the repaired parts were found to be satisfactory for service. However, field maintenance personnel also used non-standard techniques and several of these repairs were made so badly that they resulted in additional damage. In summary, with adequate training, repair instruction manuals, the proper materials and facilities, it should be possible to maintain and service advanced composite structures of increasing complexity.

3.12.6 Insurability of Advanced Composite Structures

The overall impact of all the above safety and reliability issues is an assessment of whether advanced composites, or for that matter, fiberglass reinforced structures, result in a greater hazard to society than metal structures. This is an assessment an insurance company has to make if it is to underwrite an insurance policy that is associated with a composite structure. The relative willingness of an insurance company to underwrite product liability insurance, as measured by the level of coverage and premiums, will be a measure of the perceived risk

associated with composites. If this perceived risk is significantly higher than that perceived for metal structures, insurance may be higher or insurance may not be available at all, and could prevent diffusion of composites into commerce.

3.13 ECONOMIC IMPACT

The introduction of advanced composites will have some impact in a wide number of industries as shown in Figure 3.2.

The principal industries indirectly affected by the increasing use of advanced composites will be engineering constructors and subcontractors who will provide the facilities needed to make the raw materials, and fiberglass manufacturers who will benefit from the use of hybrid composites. Impact on the metal industries will be small. Fabricators of plastics manufacturing equipment will benefit from the increasing use of advanced composites, as will educational facilities needed to train technical staffs in the requisite technology.

In terms of use of composites, the major indirect impact will be associated with the need for maintenance facilities to service privately owned vehicles. The predicted changes in fuel consumption will result in a decreased demand on petroleum products. Communications satellites will have some impact in the communications area. Depending on the growth of other space applications, such as of space power energy generation, there could be additional significant secondary impacts in this sector.

Implementation of advanced composites technology will require significant capital investments by all the directly impacted industries listed in Figure 3-2. Indirectly, impacted industries such as fiberglass manufacture, vehicle maintenance, crop storage and transportation, would also have to invest in operating facilities.

The growth of the advanced composites industry in terms of material manufacturers and users will be mainly limited by their willingness

FIGURE 3-2

Industries Impacted by Advanced Composites

MATERIAL MANUFACTURERS		COMPONENT FABRICATORS		USERS	
Direct Impact	Indirect Impact	Direct Impact	Indirect Impact	Direct Impact	Indirect Impact
			Equipment Manufacturers		
Basic Petro-chemicals	Engineering Constructors		Educational Facilities		
Plastics & Resins	Fiberglass Manufacturers	Aerospace			
		Military Systems		Armed Services	
High Performance Fiber Manufacture		Space Systems		NASA	
				Utilities	Communication
Pre-pregging		Transport Aircraft		Airlines	Petroleum Fuel
				Airports	Supporting Travel Service
(Metals)	(Metals)				
		General Aviation			
		Passenger Automobiles			Petroleum Fuel Auto Maintenance Scrap
		Trucks		Truck Transportation	Petroleum Fuel Truck Maintenance
		Agricultural Equipment		Farmers	Petroleum Fuel Crop Storage Transportation
		Recreational Boats			
		Sporting Goods			
		Miscl. (Energy Systems)		Energy Users	

to invest capital. As far as structural composite fabricators are concerned, the adaptability of existing equipment to advanced composite fabrication will minimize these capital requirements. The manufacture of advanced composite structures will be eased by the increasing use of fiberglass reinforced plastics because of commonality of equipment needs.

3.14 IMPACT ON THE LABOR FORCE

The development of advanced composites technology will have an impact on the labor force associated with each of the industries listed in Figure 3-2. Overall, this development should result in increased employment.

The skill mix required of the labor force will be similar to that required for the fabrication of fiberglass reinforced plastic structures. Production operations may require, on the average, a lower level of skills than current metal manufacturing operations. For example, to the extent that net shape parts can be fabricated fewer machinists may be required. On the other hand, increased usage of advanced composites will require that technical staffs be more highly trained, especially in terms of structural design. For example, there will be an increasing need for structural engineers capable of understanding the suttleties non-isotropic structural design. This, in turn, places requirements on universities to provide graduates with these skills. Currently only a handful of universities have programs in composite technology. If there is a shortage of practicing engineers with these skills in industry, it might be difficult to find the teachers to implement these programs. On the short term, making full time teachers out of practicing engineers could also exacerbate this skilled manpower shortage. A comprehensive program of short courses and seminars for engineers in industry, taught by industrial specialists, might be the most effective method of providing the manpower pool with the required skills.

There will be a need to train maintenance personnel in the repair and operational maintenance of advanced composite structures. These

skills could be provided at technical institutes as part of their plastics technology programs.

3.15 BALANCE OF TRADE

Currently, advanced composite structures have little impact on balance of trade because the technology still is not developed. Currently, most of the graphite composites used in the U.S. are either based on imported graphite filaments (mainly Japan) or graphite filaments made from imported PAN precursor filaments. Tungsten filament used in boron manufacture is imported, while some U.S. boron is shipped overseas. Some aramid is exported as well. Many of the prepreggers obtain their precursor resins for high temperature epoxy systems from the U.S. subsidiary of a Swiss multi-national company (Ciba-Geigy). Most of the prepreg materials currently used are made in the U.S., as are most of the composite structures in use in this country. Most advanced composite sporting goods used in the U.S. are made domestically. However, there is active international trade, with some foreign products being imported, and some U.S. products being exported.

Most of the advanced composite aerospace structures are manufactured in the U.S. An exception is Boeing Corp's. composite manufacturing facility in Winnipeg, Canada. Advanced composite aerospace structures are exported to the extent that the aerospace systems they are part of are exported. The export of military aircraft such as the F-14, F-15 and F-16 results in an export credit for advanced composites. The use of American made satellites in international or foreign communications systems also results in an export credit for advanced composites.

In the long term, advanced composites are expected to have a much stronger impact on U.S. international trade activities. As the demand for advanced composites increases, it becomes economically feasible to build integrated graphite fiber facilities in the U.S. Boron and silicon carbide fibers will be using carbon substrates in the future. In general,

importation of high performance fibers or their precursors will diminish significantly on a proportionate basis. Based on the number of papers on advanced composite technology that will be presented at the forthcoming 2nd International Conference on Composite Materials in Toronto, Canada, the U.S. has a significant lead in the design and manufacturing aspects of the technology. This should result in the U.S.'s maintaining a technical advantage in high technology products which would use significant amounts of advanced composites such as space system components, military aircraft, civilian aircraft, and possibly automotive and agricultural equipment. Consequential impacts will be reduced demand for imported petroleum fuel, and the potential for increased exports of agricultural product. Overall, it is expected that advanced composite technology will have a favorable impact on U.S. balance of trade.

3.16 TAX REVENUE

The substitution of advanced composite structures will have some consequential impact on tax revenue. The major impacts will be on revenue derived from motor fuel excise taxes. There will be some minor impacts on income derived from registration fees for motor vehicles, sales taxes and possibly income taxes.

At present, there are excise taxes on the sale of gasoline and other petroleum products used to fuel motor vehicles, on motor vehicle lubricating oil and tires and tubes, and on truck parts. While these excise taxes represent a modest cost to the user, they represent a major source of revenue to federal and state governments. These funds are used to support and maintain the highway system. A significant increase in fuel economy of automotive vehicles will result in a commensurate reduction of this revenue, unless the tax structure is altered. The current federal tax on automotive motor fuels is 4¢/gallon and is currently scheduled to be reduced to 1-1/2¢ gallon after October 1, 1978. A similar tax is imposed by every state in the union, and by the District of Columbia. These state taxes are all higher than the federal tax discussed above,

ranging from 5¢/gallon in Texas to 11¢/gallon in Connecticut. Motor fuel excise tax revenues in 1976 were $4.4 billion for the federal government and $8.8 billion for the states. To the extent that advanced composites will reduce automotive fuel consumption, they will also have an impact on this revenue.

Another revenue source that could be impacted by use of advanced composite would be registration fees for motor vehicles to the extent that they are a function of vehicle weight. In particular, trucks are taxed according to their gross vehicle weight. This revenue could be decreased to the extent that a truck of given hauling capacity could be classified in a lower gross vehicle weight class.

4.0 POLICY IMPLEMENTATION TOOLS

To date, much of the development of advanced composites technology to its current state of maturity has been due to government interest and support, mainly in the areas of space and defense. As the technology grows further, it will impact the implementation of government policy in wide areas. Conversely, the promulgation of laws and regulations in a number of diverse areas could also have significant impact on the future growth and expansion of this technology. In this section, actions by the Federal government that could have an impact on the technology are identified. These actions are principally appropriations, and laws and regulations. These include:

4.1 Appropriations

1. Military Appropriations for the acquisition of new operational systems, as well as for the support of research and development activities.
2. NASA Appropriations, for new systems acquisition and for the support of research and development.
3. Department of Energy Appropriations for the support of research and development activities related to improved energy generation systems (fusion reactors) and in energy conservation (fly wheels, electric vehicles).
4. Department of Transportation Appropriations for the support of research and development activities related to more energy efficient transportation vehicles.
5. Department of Commerce Appropriations to support the research activities of the National Bureau of Standards that are related to advanced composite structures.
6. National Science Foundation Appropriations to support the research activities of NSF that are related to advanced composite structures.

4.2 Laws and Regulations

1. Energy Policy and Conservation Act of December 22, 1975, and

subsequent regulations of the National Highway and Safety Administration (NHTSA) that pertain to the fuel economy characteristics of passenger automobiles.

2. Federal Motor Vehicle Safety Standards (49 CFR 571) and Federal Bumper Standards (49 CFR 581), which establish safety standards for passenger automobiles.
3. Federal Motor Carrier Safety Regulations (49 CRF 390-397) which establish safety standards for commercial vehicles used to carry passengers for hire, and in interstate commerce.
4. Federal Aviation Regulations which establish safety standards for aircraft. These include Certification Procedures for Products and Parts (14 CRF 21); Airworthiness Standards for Normal, Utility and Acrobatic Aircraft (14 CRF 23), Transport Category Aircraft (14 CFR 25), Normal Category Rotorcraft (14 CFR 27), Transport Category Rotorcraft (14 CFR 29), Aircraft Engines (14 CFR 33), and Propellers (14 CFR 35), as well as Noise Standards (18 CFR 36).
5. Federal Freight Car Safety Standards (49 CFR 215) and the Railroad Safety Act (45 USC 435).
6. Coast Guard Vessel Certification and Inspection Regulations (46 CFR 2.01 et. seq., 40 CFR 24, 31, 71, 91, 176).
7. Noise Control Regulations such as Occupational Safety and Health Standards (29 CFR 1910), SubPart G: Occupational Health and Environmental Control, Section 1919.95 Occupational Noise Exposure; and EPA Noise Emission Standards for Construction Equipment (40 CFR 203).
8. Occupational Safety and Health Standards (29 CFR 1910), Subpart Z. Toxic and Hazardous Substances, insofar as they relate to health hazards associated with the materials used to make advanced composites.
9. Federal Fire Prevention and Control Act of 1974 (15 USC 2218).
10. Solid Waste Act of 1976 (43 USC 3251, Title II), Guidelines for the Thermal Processing of Solid Wastes (40 CFR 240) and Guidelines for the Land Disposal of Solid Wastes (40 CRF 841), insofar as they apply to recycle or disposal of scrap advanced composite structures.

11. Federal Regulations Pertaining to Satellite Communications (47 CRF 25).
12. Economic Regulations of the Civil Aeronautics Board (14 CFR 200 et seq.).
13. Air Pollution Control Regulations such as Standards of Performance for New Stationery Sources (40 CFR 60), insofar as they create a requirement for air pollution control equipment.
14. Water Pollution Control Regulations such as Water Quality Standards and Toxic Pollutant Effluent Standards (40 CFR 20) insofar as they create a requirement for water pollution control equipment.
15. Air Pollution Regulations, such as Control of Air Pollution from New Motor Vehicles and New Motor Vehicle Engines (40 CFR 85) and Control of Air Pollution from Aircraft (40 CFR 87), insofar as advanced composites reduce the need for large engines and reduce fuel consumption per mile travelled.
16. Federal Regulations concerned with the economic aspects of agricultural production, such as Federal Crop Insurance (7 CFR 401 et seq.) Agricultural Conservation Programs (7 CFR 701+ et. seq.), Farm Marketing Quotas and Acreage Allotments (7 CFR 711 et seq.), Commodity Credit Corp. (7 CFR 1421) and Farmers Home Administration (7 CFR 1800 et seq.).
17. Defense Industrial Mobilization Regulations such as pertaining to Maintenance of the Mobilization Base (32A CFR 102), and Policy of Government Owned Plant Equipment by Private Industry (DMO-10) (32A CFR 110).
18. Export Controls on Arms, Ammunition and Implements of War (15 CFR 370, Supplement 2). At the moment, these regulations apply not only to military systems that contain advanced composite structures, but also to high performance filaments and prepregs.
19. Excise Taxes on Petroleum Fuels (26 CFR 4041, 4081, 4082).
20. Cost Accounting Standard Rules and Regulations (50 App USC 2168).

5.0 UTILIZATION OF RESEARCH RESULTS

It is expected that this report will be a useful reference document to anyone with a current interest in Advanced Composites and their applications. The cooperation obtained from the advanced composites community during the course of the study was motivated, in part, by a general desire to have available a document that considered the broad impacts of the many facets of this technology. The contributors to the study listed in Appendix A are representative of the researchers and organizations who would find this report of value.

The principal investigator has received a number of requests for briefings on his perception of the current state of the art and future of advanced composites technology from a number of government agencies.

At the request of Mr. Harold Bullis of the Congressional Research Service, the staff of the Senate Commerce Committee was briefed on April 27, 1978, on the projections for graphite filaments and composites.

At the request of Dr. S. Fishman of the Naval Surface Weapons Center, a paper will be presented at the 2nd Tri-Services Conference on Carbon Fiber Reinforced Metal Matrix Composites, to be held in Monterey, CA on May 11, 1978. The subject of the paper will be "Commercial Potential of Metal Matrix Composites."

Mr. Dell Williams of NASA Headquarters has asked the principal investigator to present the findings of this study to NASA Headquarters staff.

Dr. Richard Forman of the National Bureau of Standards, Gaithersburg, MD has asked the principal investigator to present the findings of this study to NBS management to help them in their formulation of an Advanced Composites Research Program.

Mr. Sam Powell, U.S. Department of Transportation, National Highway

Traffic Safety Administration, has asked the principal investigator to present the findings of this study to NHTSA staff working on the development of automotive fuel economy regulations.

Mr. Ken Harris of the Federal Aviation Administration of DOT met with the principal investigator several times during the course of the program and expressed continuing interest in the study.

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APPENDIX B

Mechanical Properties of Fibrous Composites

The mechanical properties of fibrous composites depend on the type of fiber incorporated in the matrix, its volumetric concentration and the relative orientation of the applied stress to the fibers. Fibrous composites are strongest and stiffest in the direction of the fibers, where the mechanical properties of the fibers predominate and fairly weak in the direction normal to the fibers where the allowable stresses are determined by the mechanical properties of the matrix material. This is a very different situation than exists for standard homogeneous materials of construction, such as aluminum or steel, that exhibit isotropic mechanical properties. Because of the directional characteristics of properties of composites, the design of components to be made from composites is more difficult, and a better understanding of the stresses this component will be exposed to in service, is required than would be the case if the components were to be made from a homogeneous material. The non-isotropic characteristic, however, can also be an asset to a designer who can tailor a composite by selectively positioning the reinforcing fibers to meet specific requirements.

In general, the mechanical properties of a fibrous composite will vary with the volumetric concentration of the incorporated fibers. The higher the fiber content, the stronger and stiffer the part, up to the point where contact and adhesion of the matrix to the fibers is impeded. If there is insufficient matrix present, voids are created which weaken the composite.

The mechanical properties tend to increase with increasing fiber length. A minimum fiber length to diameter ratio of at least 10/1 is desired. In general, however, the longer the fiber length in a given direction, the greater the continuity of stress transfer in that direction, and therefore, the greater the load bearing capability in that direction.

The way in which the fibers are arranged in a composite determines

both the direction of strength and stiffness of a composite, and also the fiber content and hence the levels of the mechanical properties that can be achieved.

High performance composites can be put to greatest advantage in applications where the stress is applied in one direction, and the component can be made from a unidirectional composite in which all the fibers are aligned in the direction of stress. The characteristic mechanical properties of representative unidirectional composites are presented in Table 2-3. As can be seen from this table, the tensile strength and tensile modulus of the various composites are much higher in the longitudinal direction parallel to the fibers than in the transverse direction perpendicular to the fibers. These can be significantly higher than those of common metals such as those listed in Table B-1.

In most composite structures, the fibers are arranged in more than one direction in order to provide better multi-directional strength properties. In bi-directional composites, laminates of fibers layers cross plied at right angles to each other have improved transverse properties when compared to a unidirectional composite, but at the expense of the longitudinal properties. This is exemplified by the data for boron-epoxy composites shown in Table B-2. A $0/90^{\circ}$ cross ply composite has only half the longitudinal (0° direction) tensile properties than a unidirectional composite, but the transverse properties are improved five fold. However, with this arrangement the in-plane shear strength is not significantly better than that of the unidirectional composite. If the composite test sample is cut in such a way that the cross plies are at $\pm 45^{\circ}$ to the applied stress, significantly improved shear properties are obtained, but at the cost of longitudinal and transverse properties. A standard method of obtaining a composite with quasi-isotropic properties is to cross-ply the fiber layers at $0^{\circ}/90^{\circ}/\pm 45^{\circ}$. Properties of representative quasi-isotropic composites are given in Table B-3.

Multidirectional composites are usually made by placing fiber strands

TABLE B-1

Tensile Properties of Representative Metals

Material		Aluminum		Steel	Titanium	Lead
Alloy		7075-0	7075-T6	SAEQ980	6Al-4V	
Density	lbs/in^3	0.100	0.100	0.289	0.160	0.41
	gr/cm^3	2.72	2.72	7.96	4.24	11.3
Ultimate Tensile Strength	$10^3 psi$	32	72	95-115	138	
	MPa	221	524	655-795	952	
Tensile Yield Strength	$10^3 psi$	14	67	80	128	2
	MPa	97	462	550	883	13.8
Tensile Modulus	$10^6 psi$	10.4	10.4	28	16.5	2
	GPa	72	72	193	114	13.8
Specific Tensile Yield Strength	$10^3 in$	140	670	276	800	5
	$10^3 cm$	360	1700	700	2030	13
Specific Modulus	$10^6 in$	104	104	97	103	5
	$10^6 cm$	260	260	240	260	13

TABLE B-2

Effect of Composite Structure on the Mechanical Properties of 4mil Boron/Epoxy Composites

Fiber Direction		Unidirectional (0^o)	$0/90^o$ Crossply	$\pm 45^o$ Crossply
Fiber Tensile Strength	10^3psi	450	450	450
Fiber Tensile Modulus	10^6psi	55	55	55
Volume % Fiber		50	50	50
Composite Properties				
Longitudinal (0^o) Properties				
Tensile Strength	10^3psi	186-232	94-108	22-35
Tensile Modulus	10^6psi	29.6-32.0	17.2-18.2	3.8
Compressive Strength	10^3psi	443-460	172-225	35-43
Compressive Modulus	10^6psi	35.0-35.5	17.8	3.98
Poisson's Ratio		0.20	0.05	0.85
Transverse (90^o) Properties				
Tensile Strength	10^3psi	9.8-17.8	94-108	22-35
Tensile Modulus	10^6psi	3.16-3.92	17.2-18.2	3.8
Compressive Strength	10^6psi	42-49	176-225	35-43
Poisson's Ratio		0.02	0.05	0.85
Inplane Shear Strength	10^3psi	18.7	18.9-29.0	66
Inplane Shear Modulus	10^6psi	1.82	0.83-1.08	-

Source: Technical Data SP-292 Boron Filament Prepreg. Scotchply Advanced Composite Structural Material, 3 M Company, St. Paul, MN, SP-RACI(81.1)R (Sept. 1, 1971)

TABLE B-3

Comparison of Tensile Properties of Glass and Graphite Quasi-Isotropic Epoxy Composites

Fiber		E Glass	Graphite	Graphite
Grade			Celion 3000	HMS
Supplier		3-M*	Celanese	Hercules
Fiber Volume %		45	62	60
Density	lbs/in^3	0.065	0.057	0.059
	g/cm^3	1.8	1.57	1.63
Tensile Strength	Ksi	57	77.4	50
	M Pa	393	534	345
Tensile Modulus	$psi x 10^6$	2.6	7.4	10.6
	G Pa	18	51	73

* Type 1002 Pre-preg

randomly in the matrix so as to achieve isotropic properties. Such composites are usually made by incorporating a fiber mat of chopped strand in the matrix. While incorporating chopped fibers into the matrix will significantly improve the mechanical properties of the resulting composite over those of the matrix, as shown in Table B-4, because of the difficulties in incorporating a higher fiber loading, the mechanical properties of this type of composite are lower than those attained with directional fibers.

Advanced composites also include "hybrid composites: which combine two or more different types of fibers in a common matrix. Hybridization greatly expands the range of properties that can be achieved with composites. In these hybrids, the various fibers each contribute additively to the properties of the resulting composite. Representative mechanical properties of a set of graphite-aramid hybrid composites are presented in Table B-5.

TABLE B-4

Properties of Various Thermoplastic Composites

RESIN		NYLON 6-6					POLYSULFONE			POLYESTER			FIBERS	
Reinforcement		Unreinforced	Carbon	Carbon	Carbon	Glass	Unreinforced	Carbon	Glass	Unreinforced	Carbon	Glass	Carbon	Glass
Loading , %		0	20	30	40	40	0	30	30	0	30	30		
Specific Gravity		1.14	1.23	1.28	1.34	1.46	1.24	1.45	1.37	1.32	1.52	1.47	1.8	2.54
Tensile Strength	Ksi	11.8	28.0	35.0	40.0	31.0	10.2	18.0	23.0	8.0	19.5	20.0	300	500
	M Pa	81	193	242	276	214	70	124	159	55	135	138	2510	3450
Tensile Elongation	%	10	3-4	3-4	3-4	2-3	50-100	3-4	2-3	10	3-4	2-3	1.2	4.8
Flexural Strength	Ksi	15	42	51	60	42	15.4	24.0	32.0	13.0	28.0	29.0		
	M Pa	104	290	352	414	290	106	166	221	90	193	200		
Flexural Modulus	10^6 psi	0.4	2.4	2.9	3.4	1.6	0.4	1.2	2.1	0.4	1.4	2.0		
	M Pa	2800	16000	20000	2300	1100	2800	8300	1450	2800	9600	14000		
Shear Strength	Ksi	9.6	12.0	13.0	14.0	12.0	9.0	9.5	9.5	7.0	8.0	8.0		
	M Pa	66	83	90	97	83	62	66	66	48	55	56		
Heat Distortion Temperature at 264 psi	^oF	150	495	495	500	500	345	365	365	155	430	430		

Source: "Carbon Fibers Add Muscle to Plastics", Machine Design, February 7, 1974

TABLE B-5

Mechanical Properties of Unidirectional
Graphite/Aramid Hybrid Epoxy Composites

Percentage Thornel 300 Graphite Fiber		100	75	50	0
Percentage Kevlar 49 Aramid Fiber		0	25	50	100
Total Fiber Volume Fraction		0.60	0.60	0.60	0.60
Specific Gravity		1.60	1.56	1.51	1.35
Tensile Modulus	10^6 psi	21.1	17.4	15.7	11.2
	G Pa	145	120	108	77
Tensile Strength	Ksi	227	186	176	183
	M Pa	1.56	1.28	1.21	1.26
Compressive Strength	Ksi	146	136	99.8	41.5
	M Pa	1000	938	688	286
Flexure Strength	Ksi	233	197	160	91.9
	M Pa	1610	1360	1100	634
Short Beam Shear Strength	Ksi	13.2	11.0	8.1	7.1
	M Pa	92	76	56	48

Source: C.H. Zweben,"Hybrid Composite Materials," Proc. I.C.C.M. p. 345 (1976)